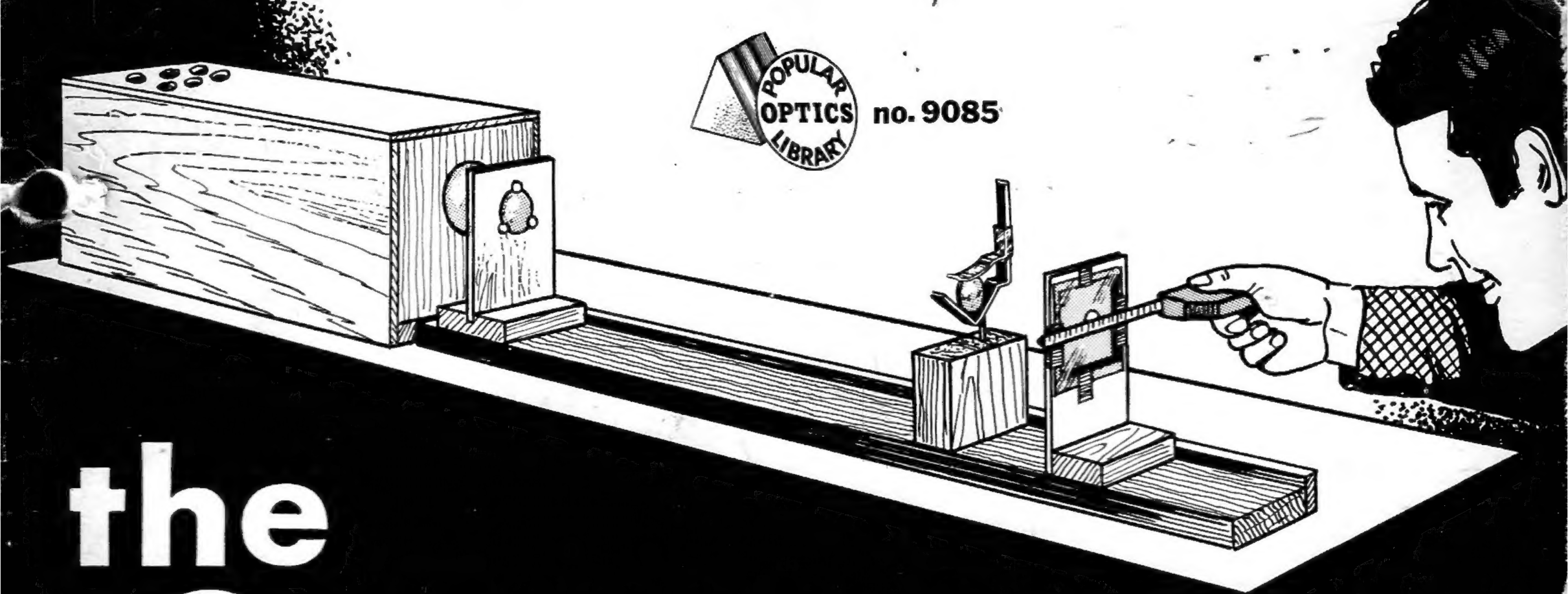
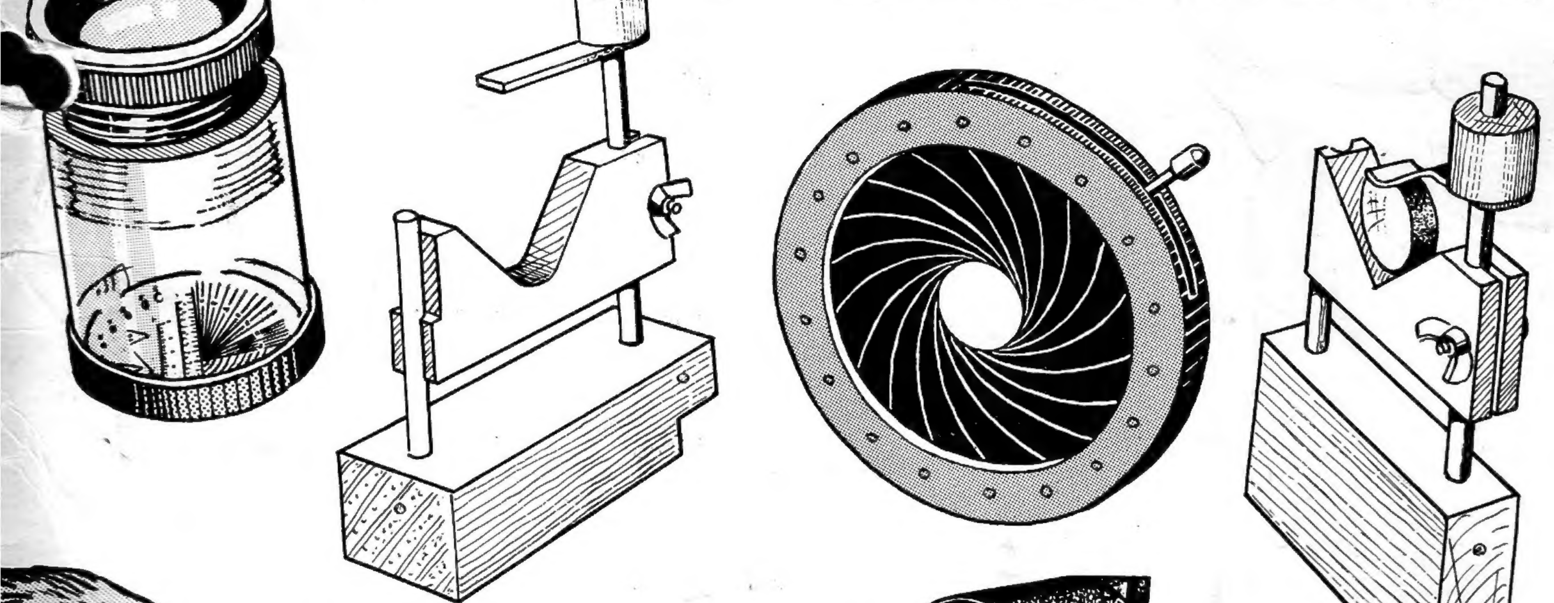
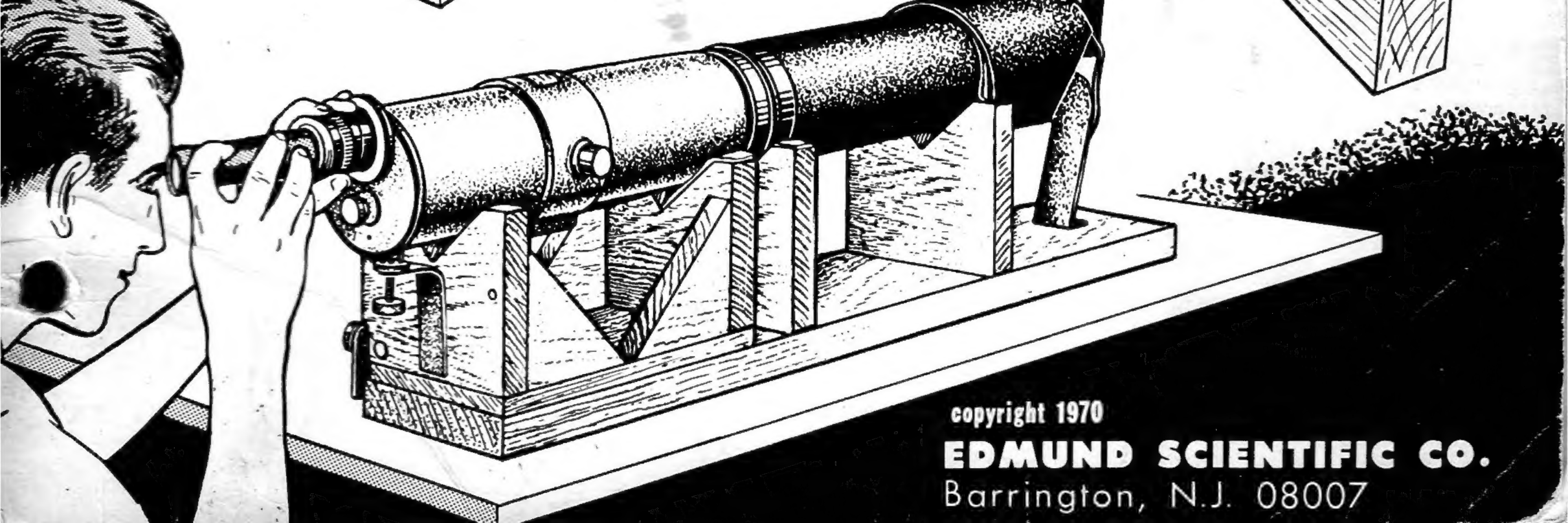


POPULAR OPTICS LIBRARY no. 9085

the OPTICAL BENCH

Edmund & Brown





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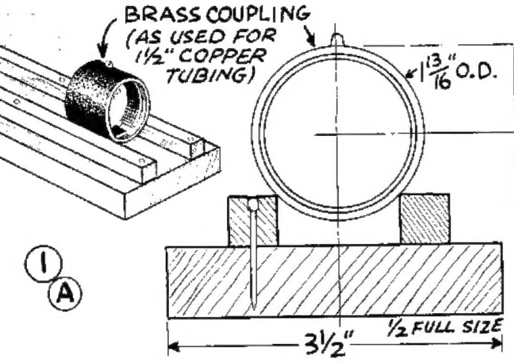
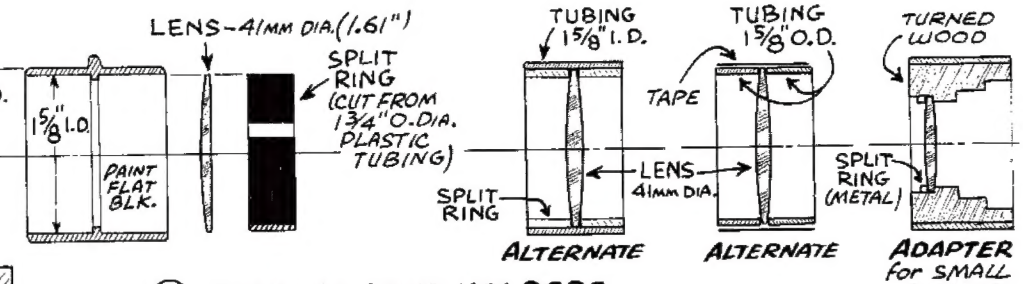


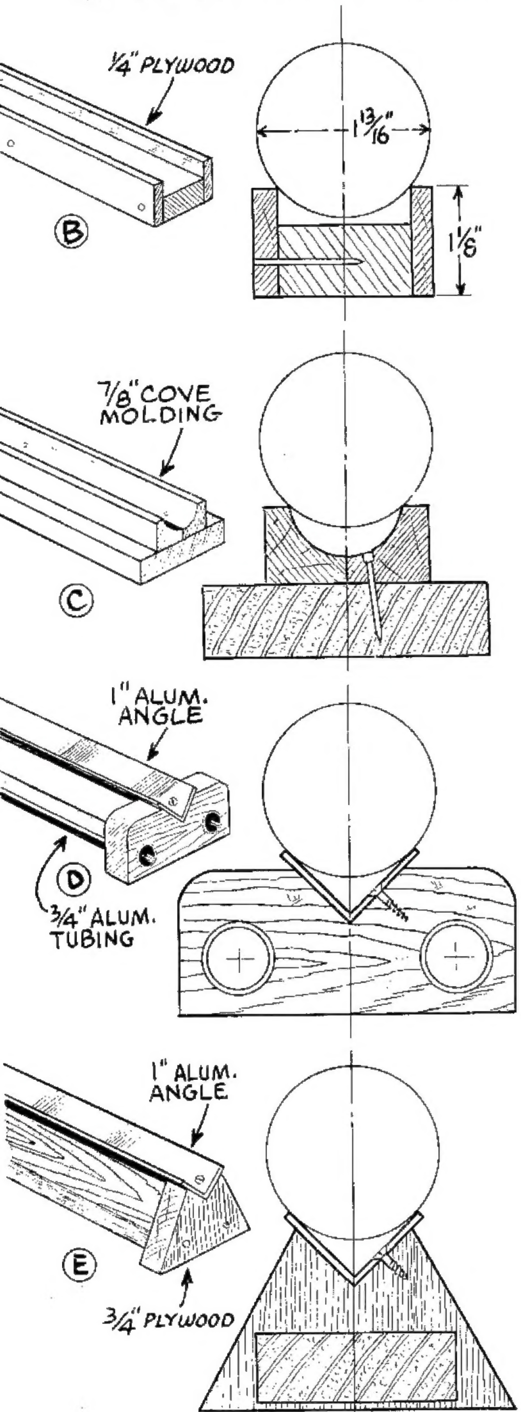


② TUBULAR LENS HOLDERS

LOW BENCH WITH ONE-SIZE TUBULAR LENS HOLDERS IS SIMPLEST TYPE TO MAKE

The OPTICAL BENCH

by N.W. Edmund and Sam Brown



ALL SECTIONS ½ FULL SIZE

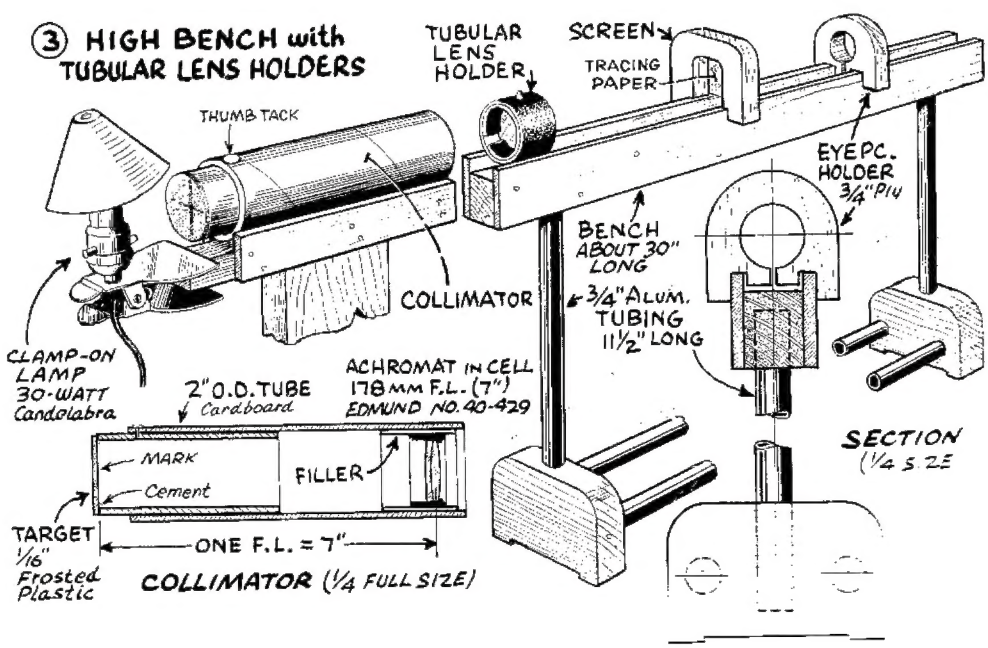
AN OPTICAL bench is any bed or track on which lenses and other optical parts can be mounted for experiments, testing or demonstrations. Such a piece of equipment can be made in a thousand different ways and may cost anything from 50¢ to many hundreds of dollars. The various lenses used are mounted in lens holders of some kind, and it is this one item--the lens holder--which more or less determines the convenience and cost of the whole setup.

SIMPLEST CONSTRUCTION. The simplest bench is one to be used with a suitable assortment of lenses, all of which are the same diameter. This permits the use of tubular holders made of plastic or metal tubing, Fig. 2, while the bench itself can be a vee or any other form of two-point support, as shown in Fig. 1, A to E. For a suitable "kit" of lenses, you might choose "close-up" lenses, 41mm (1.61") diameter.

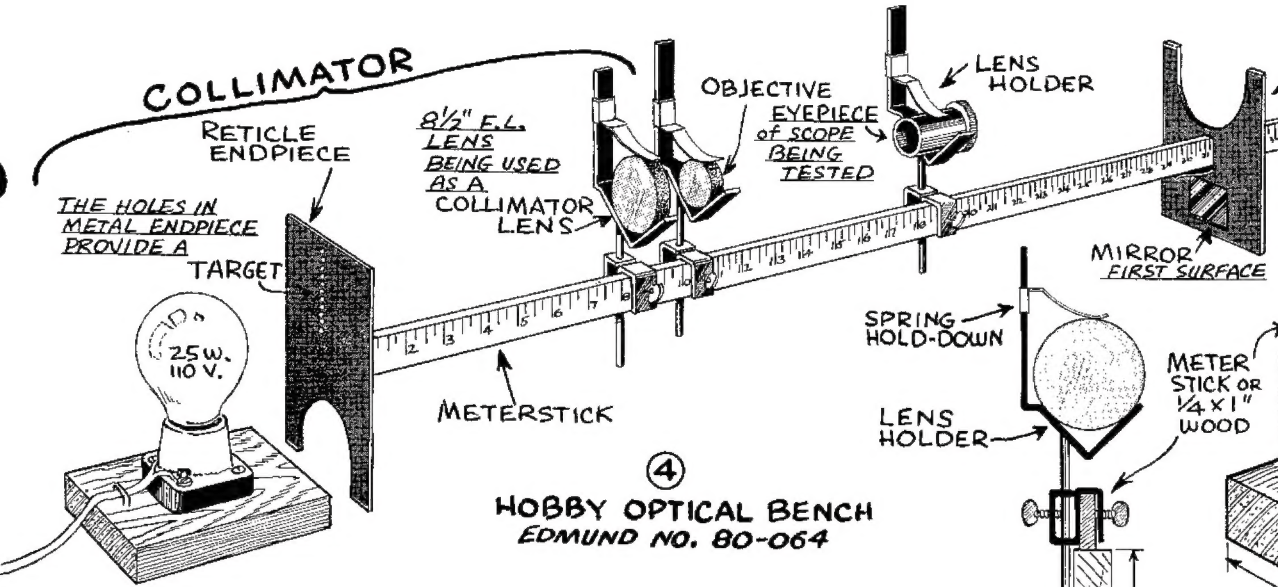
You will quickly note two construction faults. First, the bench is too low and must be raised an additional 12 to 15 inches to provide a comfortable sighting level for a person seated or standing. Even worse is the scant clearance between your face and the bench, making it difficult and uncomfortable to look through a lens setup except from the one good position directly behind the bench.

The too-low bench is readily corrected by placing the low bench

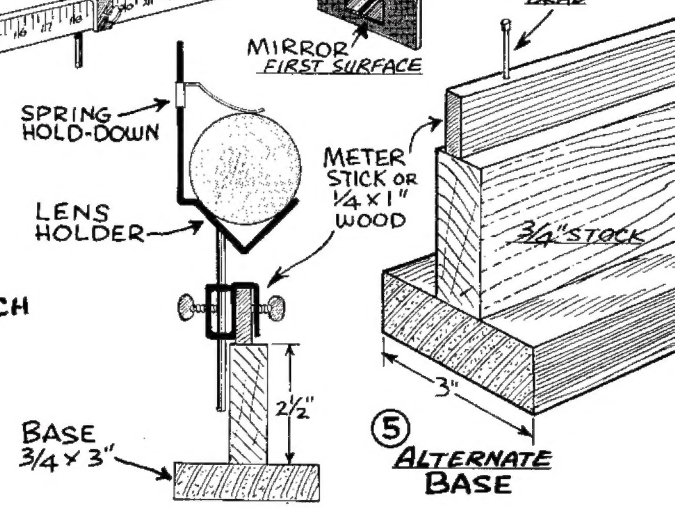
③ HIGH BENCH with TUBULAR LENS HOLDERS



COLLIMATOR (¼ FULL SIZE)



4
HOBBY OPTICAL BENCH
EDMUND NO. 80-064



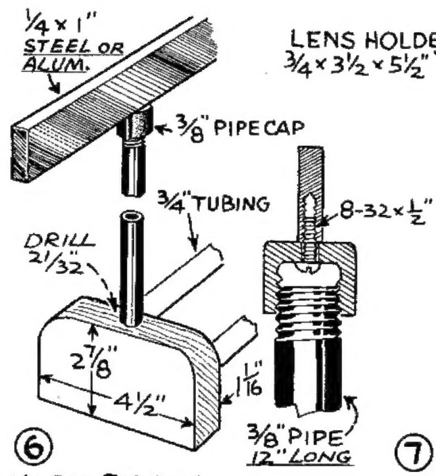
5
ALTERNATE BASE

on a box or other support. Alternately, you can build a high bench right from the start, a typical design being as shown in Fig. 3. However, the fault of scant eye clearance remains. Common to every lens bench above toy grade is a collimator. This useful piece of equipment gives you the equivalent of a distant target right at the bench. The one shown in Fig. 3 nestles in its own separate bed. The collimator itself--lens, light and tube--can be built for about $4.

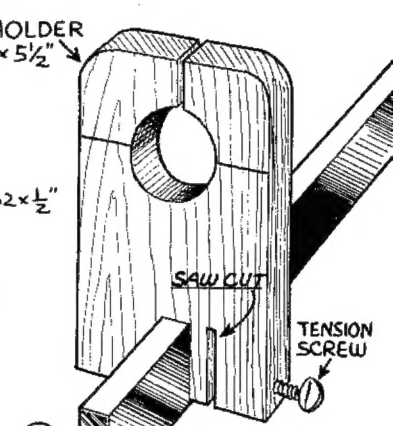
HOBBY OPTICAL BENCH. Fig. 4 shows a simple type of manufactured optical bench with adjustable lens holders. Other features include a target plate, and a sliding reversible leg with a first surface mirror to be used for auto-collimation (see page 10). The target is converted to a collimator by placing any achromat in front of it at one focal length, testing the spacing by auto-collimation.

The bed of the hobby optical bench is a meter stick, 40 inches long. It is somewhat light and shaky, also too low, all of which can be corrected by additional construction, Fig. 5. Lens holders can be purchased separately for mounting on your own bench, Fig. 6, or, you can make your own non-adjustable holders of wood to fit the meterstick or other monorail bed, Fig. 7.

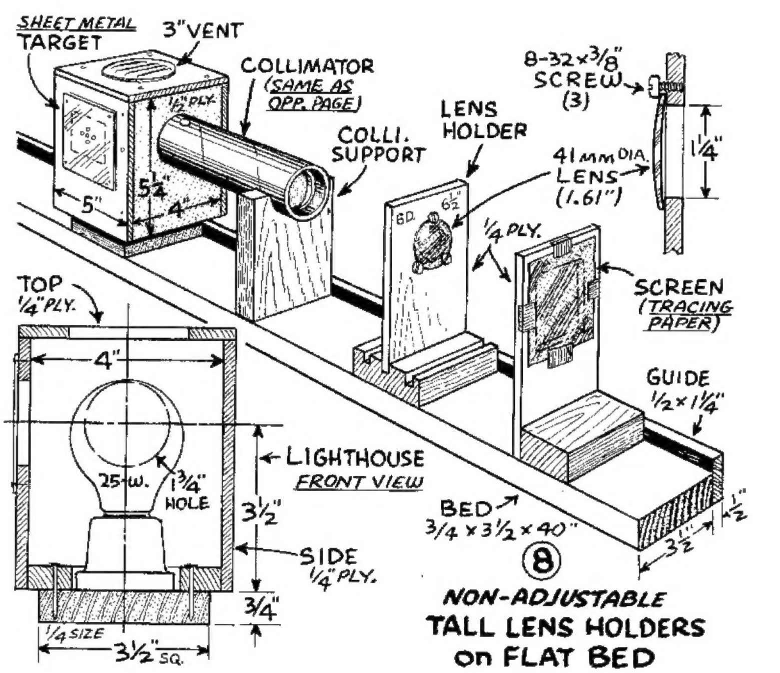
TALL LENS HOLDERS. The scant eye clearance of the tubular type of lens holder is avoided by making tall holders of plywood, Fig. 8. Although non-adjustable for height, this style is comfortable to use and has merit in easy, low-cost construction. When you discard the tubular holder, the 2-point support of the vee bed is of no value, and may be replaced by a simple flat bed with one guide rail, as shown. The plywood lighthouse can be turned to put any of its four



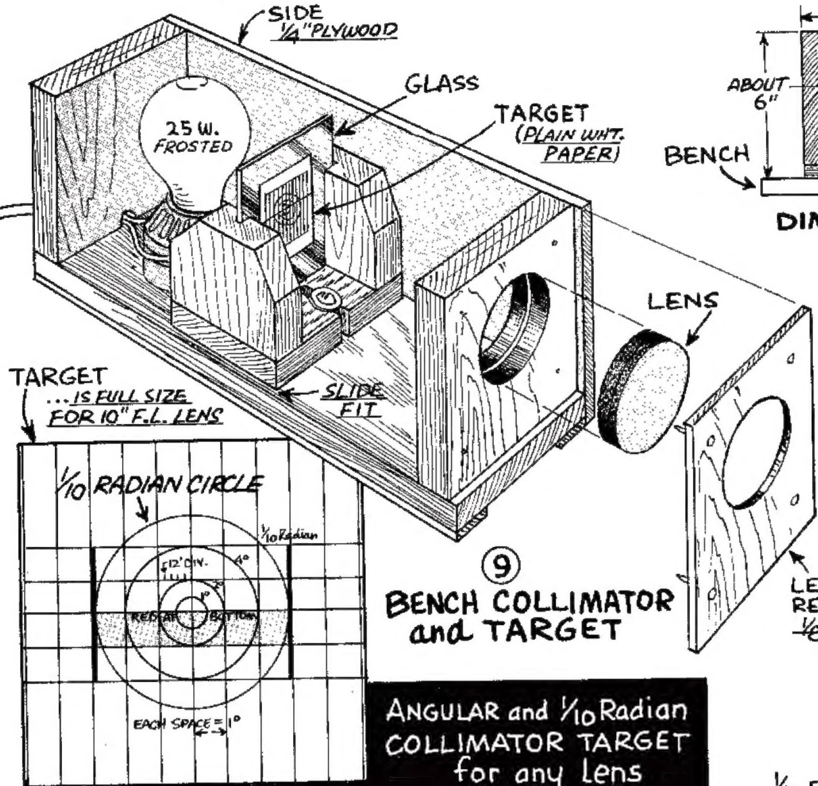
6
HIGH BENCH with METAL BED



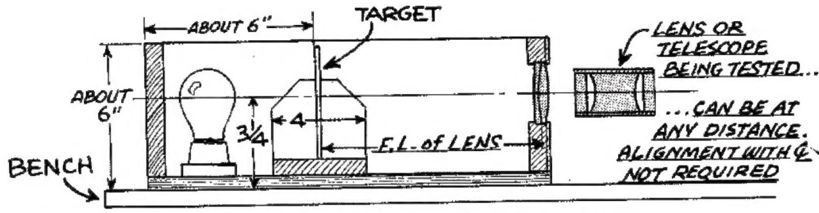
7
ONE-SIZE LENS HOLDER



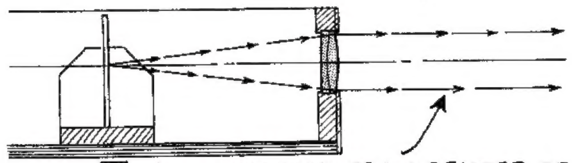
8
NON-ADJUSTABLE TALL LENS HOLDERS on FLAT BED



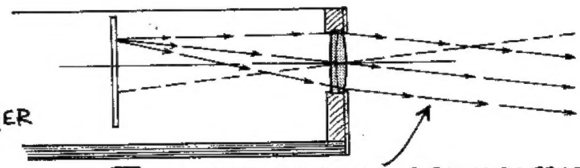
⑨ BENCH COLLIMATOR and TARGET



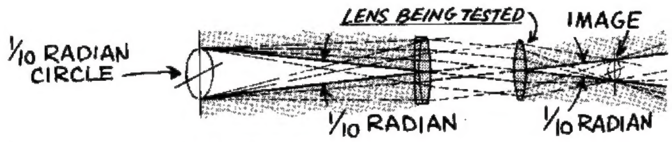
DIMENSIONS DEPEND ON F.L. OF LENS



[A] ALL LIGHT RAYS FROM CENTER OF TARGET EMERGE PARALLEL



[B] ALL LIGHT RAYS FROM A POINT AT EDGE OF TARGET EMERGE PARALLEL



[C] ANY ANGLE OF THE TARGET WILL BE MAINTAINED THRU ANY LENS BEING TESTED

ANGULAR and 1/10 Radian COLLIMATOR TARGET for any lens

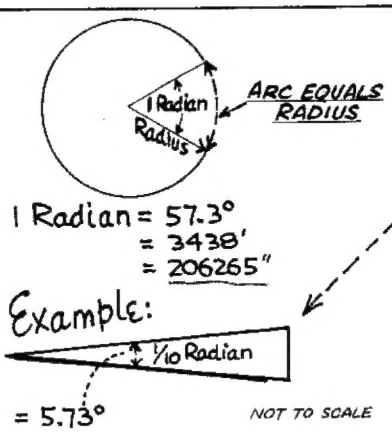
	You want to find	FORMULA	Ex: 20" F.L. COLLI. LENS
MAKING THE TARGET	DIA. OF $\frac{1}{10}$ Radian CIRCLE	DIA. = F × $\frac{1}{10}$	$20 \times \frac{1}{10} = \frac{20}{10} = 2''$
	DISTANCE EQUAL TO 1°	1° SPACE = F × .0175	20 × .0175 = .35"
READING THE TARGET	TRUE ANGULAR FIELD OF A TELESCOPE	SIMPLY COUNT THE DEGREE SPACES — Example is ABOUT 3½°	
	F.L. OF ANY POSITIVE LENS OR EYEPIECE	F = DIA. OF 1/10 Radian CIRCLE [1] times 10	Ex: 2" F.L. LENS THE IMAGE OF CIRCLE WILL READ .200" = 2" F.L.
	ALTERNATE: for Lenses over 10" F.L.	F = IMAGE SIZE OF 1° SPACE times 57	Same Ex. WILL READ .035" AT IMAGE .035 × 57 = 1.995"
	[1] IMAGE OF TARGET CIRCLE CAN BE MEASURED EXACTLY WITH A SCALE MAGNIFIER		

sides toward the test setup, meaning you can have as many as four different targets.

HOMEMADE COLLIMATORS. A collimator lens is something like a telescope objective--the bigger the better. About 3 in. diameter and 24 in. f.l. is a good size, suitable for some tests on telescopes as large as 6-inch aperture. However, any smaller achromat is satisfactory for most operations. Usually you will want the target to be something more sophisticated than a plain crossline, and the common choice is a target

RADIAN Measure

If you draw a circle and set off the radius around the circumference, the angle so enclosed will be 1 radian. It can be seen that if 1 radian equals one radius, then, 1/10 radian, for example, will be 1/10 of the radius. Using this idea, you can work most problems concerning slender angles without using trig tables.



1 Radian = 57.3°
= 3438'
= 206265"

Example: = 5.73°

Conversions

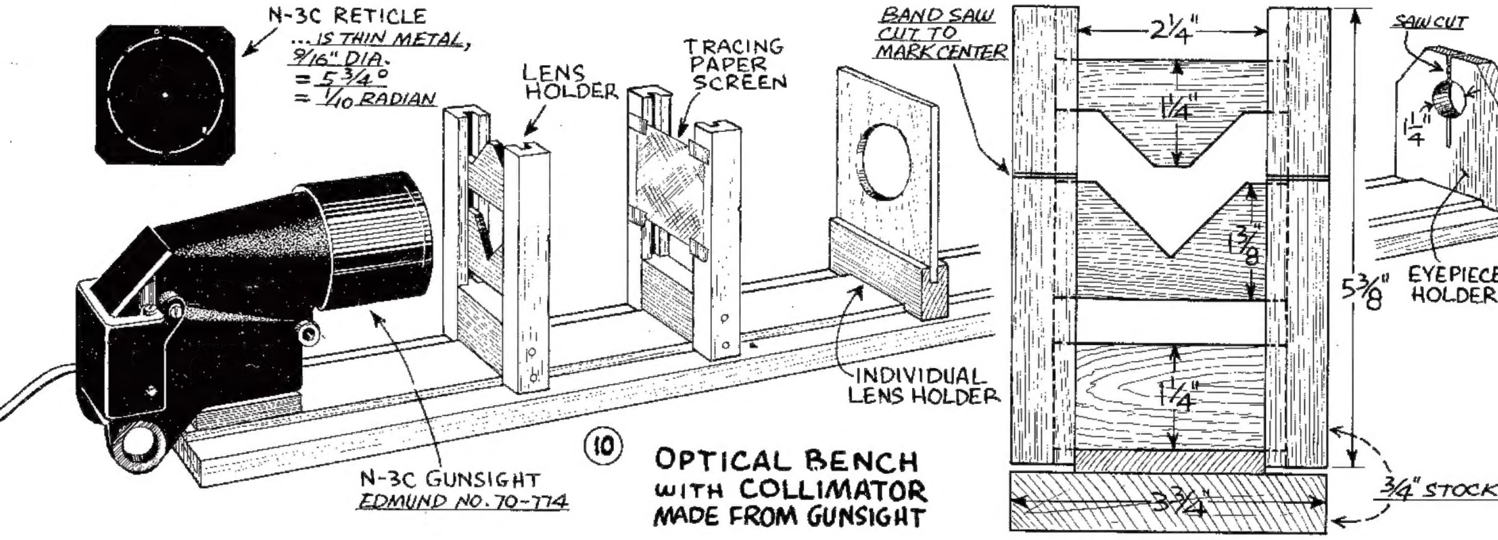
in DEGREES, MINUTES or SECONDS as desired

[1] RADIANS to ANGULAR MEASURE = ANGLE IN Radians × 1 Radian

Ex. ANGLE IN DEGREES $= \frac{1}{10} \times 57.3 = \frac{57.3}{10} = 5.73°$

[2] ANG. MEASURE TO RADIANS $= \frac{\text{ANGLE}°}{57.3}$ or $\frac{\text{ANGLE}'}{3438}$ or $\frac{\text{ANGLE}''}{206265}$

Ex. ANGLE IN RADIANS $= \frac{5.73°}{57.3} = .1$ Radian (1/10)



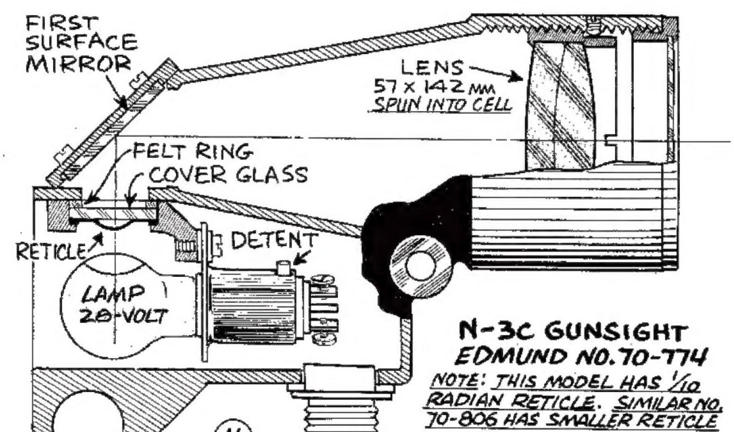
(10) OPTICAL BENCH WITH COLLIMATOR MADE FROM GUNSIGHT

with angular scale and 1/10 radian circle. Rules for making and using this target are given in Fig. 9. The target is drawn with black ink on white paper; it is taped to a piece of glass, as shown.

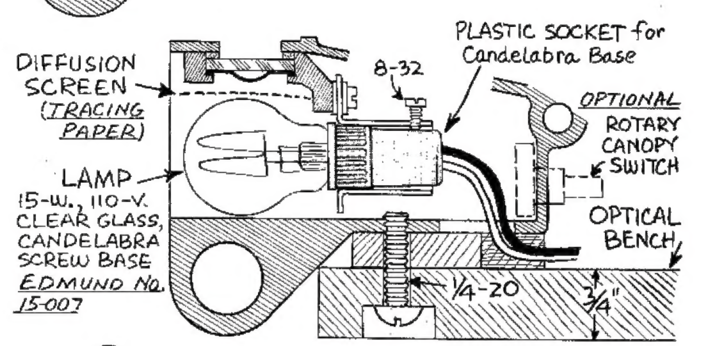
Light from any distant object reaches your eye in parallel bundles. In the same manner, light emerges from the collimator in parallel bundles, as shown at A, B and C, Fig. 9, producing the same effect as a distant target. All of the light is in parallel bundles, but the whole light cone is spreading, diverging. In other words, parallel light does not mean quite the same thing as a parallel "beam of light."

Various military collimators are available at bargain prices from time to time; the many inexpensive collimator gunsights are essentially collimators and are easily adapted for bench use, as shown in Figs. 10, 11, and 12. The unit shown is especially good for measuring the focal length of eyepieces.

ADJUSTABLE LENS HOLDERS. One common kind of adjustable lens holder is based on the tongue-and-groove principle, Fig. 10. You know very well the slides will be either too loose or

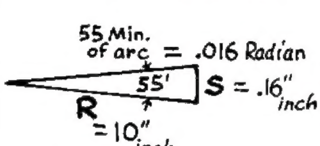


(11)



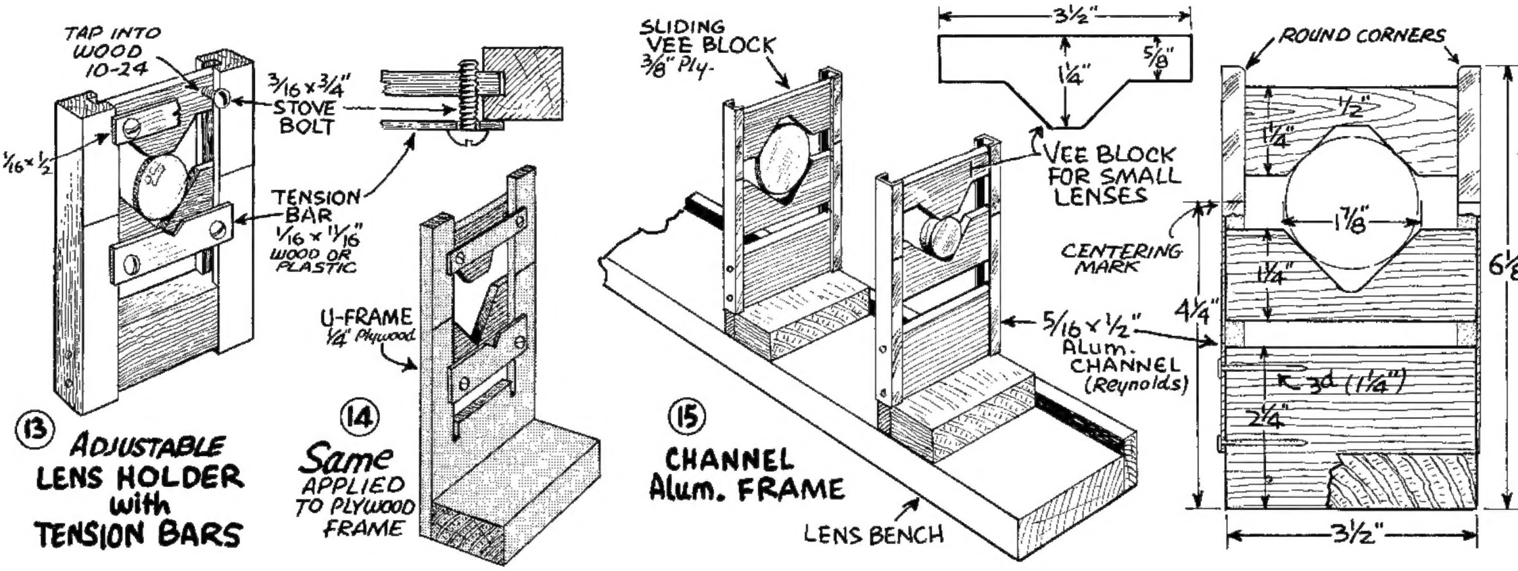
(12) CONVERSION TO 110-VOLT LIGHTING

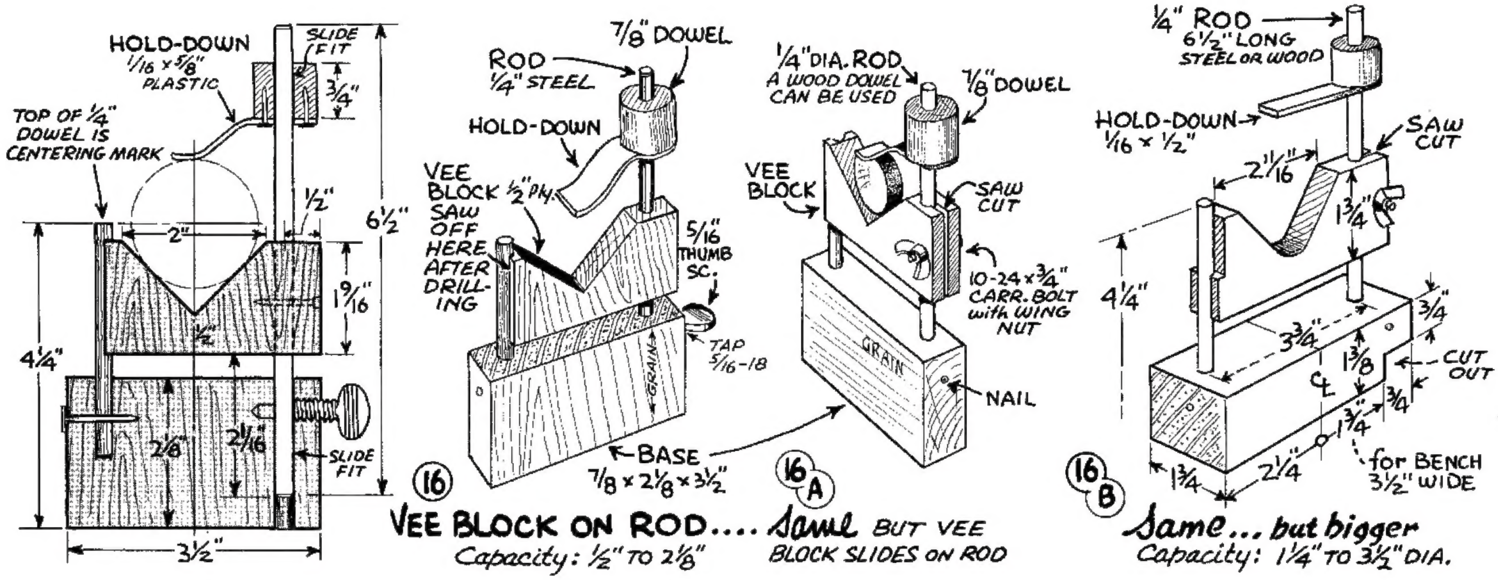
Radian Formulas



Example NOT TO SCALE

When ANGLE IS GIVEN IN DEGREE MEASURE	Example	When ANGLE IS GIVEN IN RADIANS — PART OF THE CALCULATION IS ALREADY DONE and FORMULAS ARE SIMPLER	
3 $S = \frac{\text{ANGLE} \times R}{1\ \text{Radian}}$ (Deg., Min., or Sec.)	$\frac{55 \times 10}{3438} = \frac{550}{3438} = .16''$ inch	6 $S = \text{ANGLE} \times R$ (ANGLE in Radians)	$.016 \times 10 = .16''$ inch
4 $R = \frac{S \times 1\ \text{Rad}}{\text{ANGLE}}$ (Deg., Min., Sec.)	$\frac{.16 \times 3438'}{55'} = \frac{550}{55} = 10''$ inch	7 $R = \frac{S}{\text{ANGLE}}$ (ANGLE in Radians)	$\frac{.16}{.016} = 10''$ inch
5 $\text{ANGLE} = \frac{S}{R}$ (ANGLE in Radians)	$\frac{.16}{10} = .016$ Radian	1 $\text{ANGLE} = \text{ANGLE} \times 1\ \text{Rad}$ (ANGLE in ANG. MEASURE = ANGLE in Rad × 1 Rad)	$.016 \times 3438 = 55'$ Min. of arc





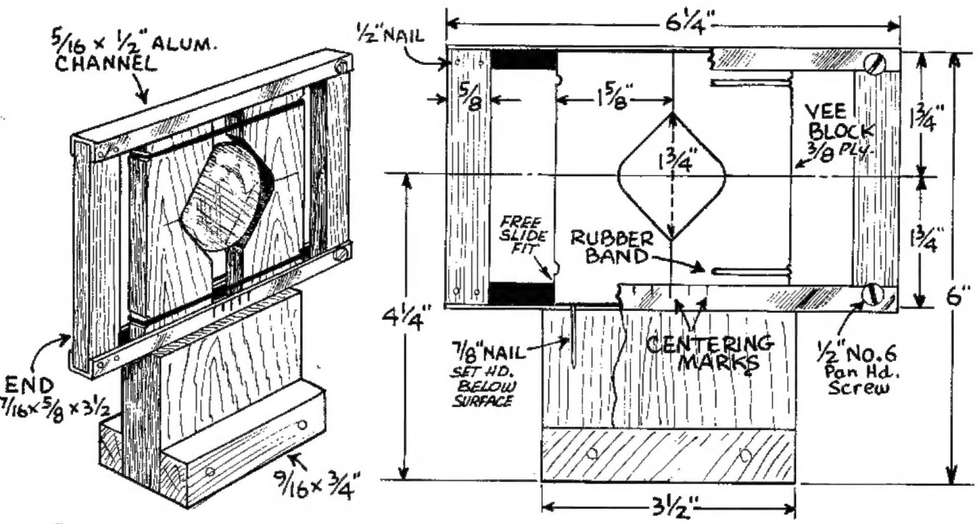
too tight at times, but with a little wetting or waxing when needed, this kind of lens holder works fairly well. If the slide action becomes hopeless, you can add positive tension with a tension bar, as shown in Fig. 13. It can be seen this idea would work nearly as well on a simple plywood frame, Fig. 14, eliminating the groove entirely. However, the plywood frame does not automatically hold the vee blocks in a horizontal level position; a shallow rabbet at the ends of the vee blocks would correct this.

Simple and practical lens holders can be made of plastic or metal channel molding, Fig. 15. The specific product shown is Reynolds 1/2 in. wide aluminum channel; it is a simple matter to squeeze or hammer the molding to grip 3/8 in. plywood vee blocks.

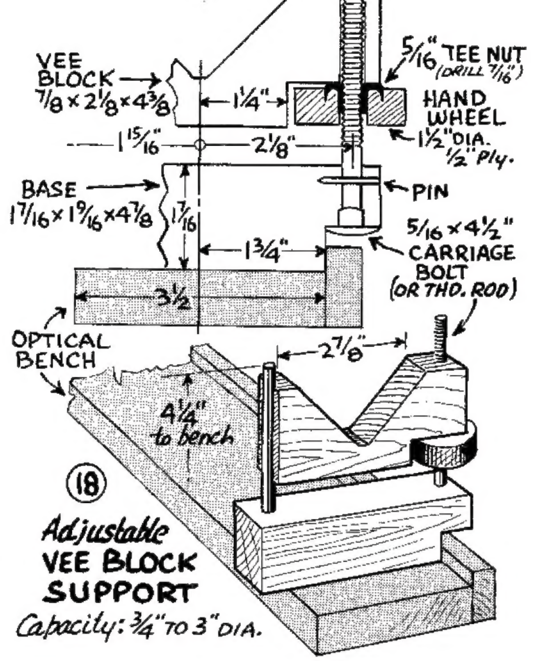
For something a little better, the idea of having the vee blocks slide up and down on a rod is a favorite seen on many amateur and professional lens benches. In Fig. 16 design, the lower vee block is permanently attached to the rod, while the rod itself slides in the base. The rod may be clamped if needed by means of a thumb screw tapped into the side grain of the wood base, as shown. The top hold-down is a strip of springy plastic or metal; it will stay put when you press it down on top of the lens.

The more common vee block-on-a-rod has the vee block sliding on the rod, Fig. 16A. This style is a trifle less convenient to center, but the advantage is small. The width can be increased to handle bigger lenses, Fig. 16B. The optical centerline is specified at 4-1/4-in. which is a good standard, permitting plenty of room for the side of your face above the surface of the bench. The top of the left-hand rod is your guide for centering the lens in the holder--the center of the lens should be approximately level with the top of the rod. Needless to say, the collimator and all other bench fixtures must have the same optical centerline.

The job of centering the lens in the lens holder is easier and more exact with the vee blocks



(17) CROSS SLIDE VEE BLOCKS - *Capacity: 1 1/4" to 2 1/2"*



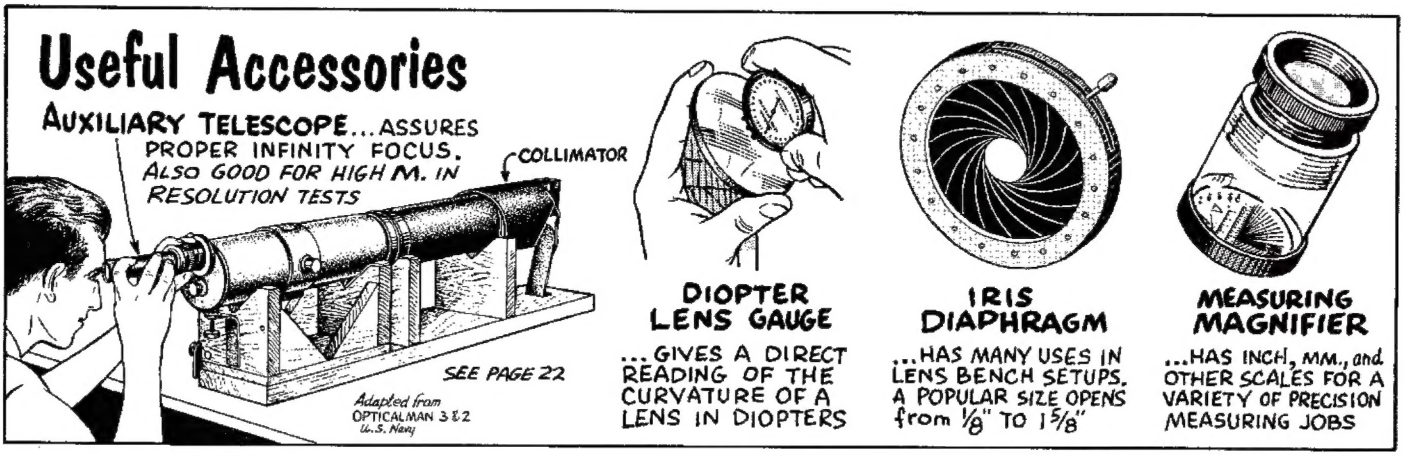
(18) *Adjustable* VEE BLOCK SUPPORT *Capacity: 3/4" TO 3" DIA.*

working on a cross slide, as shown in Fig. 17. The slides are a free slide fit in the channel molding, the slight tension needed to hold the lens being supplied by the two rubber bands.

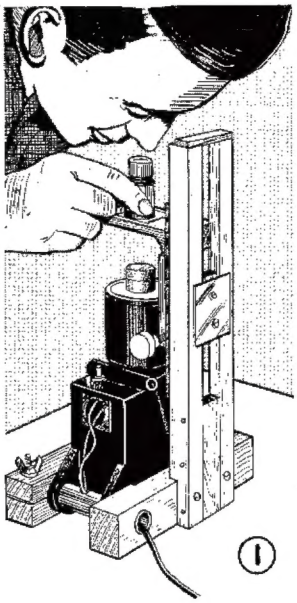
Fig. 18 shows a useful variation of the vee block-on-a-rod construction, with a handwheel added for adjustable height. A pair of these supports will handle tube assemblies and complete telescopes. A single unit is useful for holding a measuring magnifier, providing the up-and-down movement often needed to put the desired reticle scale in line with the exit pupil or other aperture or part you are measuring. A top hold-down can be added if desired. Also, it will be apparent a handwheel could be added to any of the three Fig. 16 designs.

BENCH INSTALLATION. Any low optical bench must be raised an additional 12 to 15 inches to put the optical centerline at a height of about 4 ft. above the floor. This level is comfortable for a person seated, and requires only a slight stoop if you are standing. The needed elevation can be obtained with a couple wood or even cardboard boxes. If you want something better, a narrow cabinet can be made to rest on top of a bench or table. This can have shelves, drawers, etc. as desired. A cabinet of this kind provides space to fold the light path of a long focal length collimator lens, using a good quality first surface mirror. A bench installed on a wall shelf is entirely practical and costs very little to install. For such installation the bench should have the collimator at the left as you face it, assuming the eye you use for monocular vision is the right one. To a lesser extent, this item about right-eyed or left-eyed should be kept in mind when making any installation.

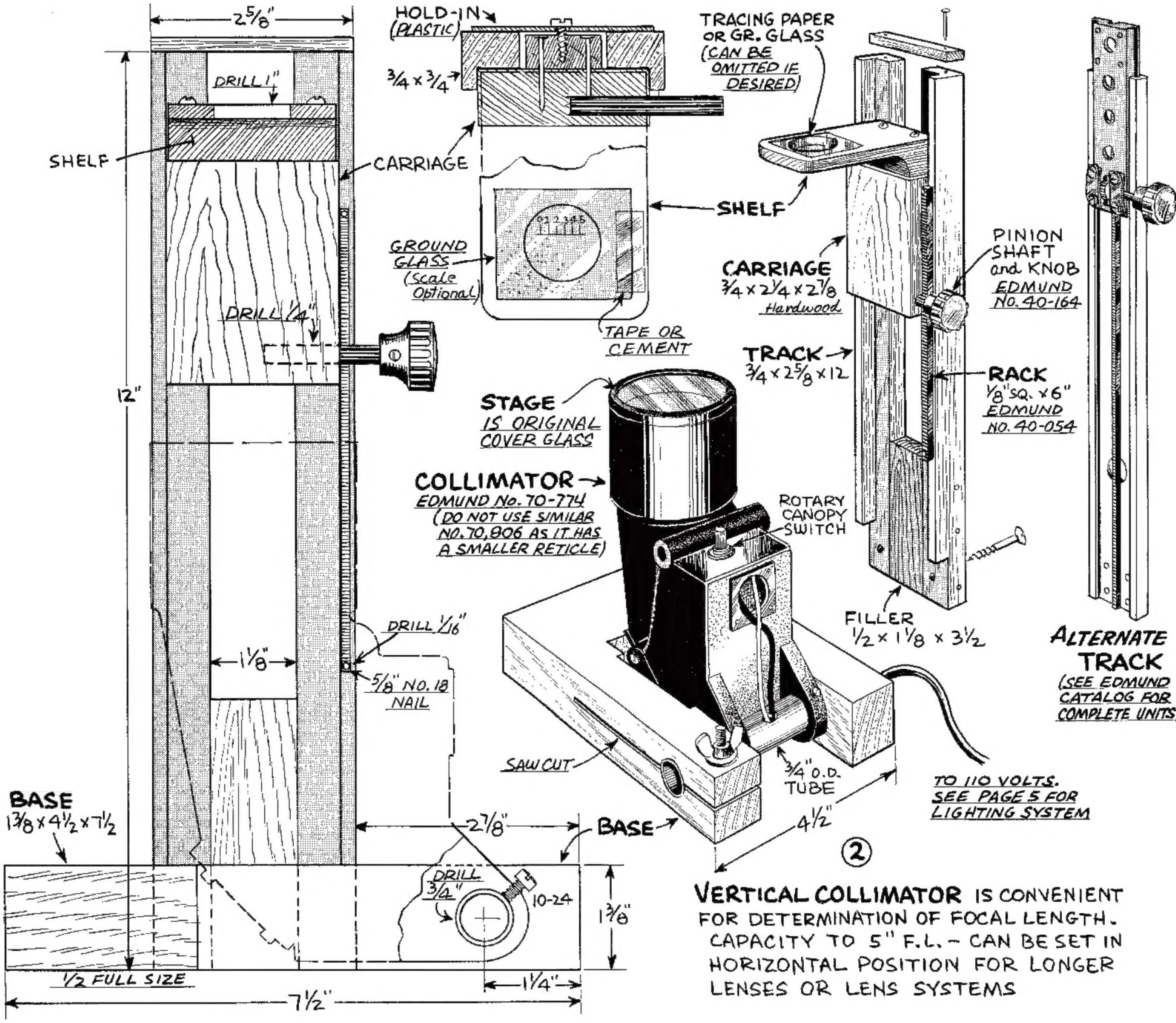
USEFUL ACCESSORIES. Of the useful accessories shown below, the measuring magnifier is of first importance and the adjustable iris second. Two iris diaphragms are a convenience. The auxiliary telescope is often useful and is easily made from surplus achromats--a typical design is shown on page 22. A lens gage is a luxury you can do without, although at times a great help, especially if you use the diopter system.



Finding the Focal Length



FINDING the focal length of a lens or eyepiece is such a frequent operation that special instruments are used solely for this purpose. Such a unit is the vertical collimator shown in Figs. 1 and 2. It is the same military gunsight described on a previous page, the only difference being the vertical mounting. The vertical orientation has the useful feature that any lens or eyepiece you want to check is simply placed on the level stage--no lens holder is needed. The measuring magnifier, also, is supported on a level shelf, as can be seen in Fig. 1. The shelf can be covered with a piece of ground glass or tracing paper, but it is also practical to sight through the open hole. Normally the measuring scale is the magnifier reticle, but if desired you can make your own scale on tracing paper, which is then read with an ordinary magnifying glass. If you do not use a ground glass to pick up the target image,



② VERTICAL COLLIMATOR IS CONVENIENT FOR DETERMINATION OF FOCAL LENGTH. CAPACITY TO 5" F.L. - CAN BE SET IN HORIZONTAL POSITION FOR LONGER LENSES OR LENS SYSTEMS

it is doubly important to have the measuring magnifier properly adjusted in focus for your eyes to avoid parallax.

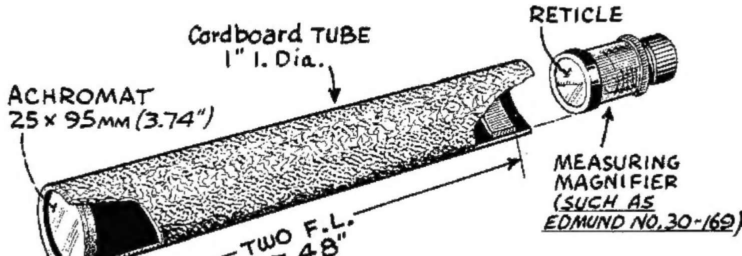
In use, the movable shelf supporting the magnifier is racked up or down until you see the 1/10 radian collimator circle sharply in focus, superimposed on the reticle of the magnifier. The diameter of the target image is then read on the scale to the nearest .005 inch. Whatever the reading, you multiply it by 10 to get the focal length of the lens being tested. Since the scale on the average measuring magnifier is .5 inch long, it means you can measure lenses to 5 inches focal length. For longer lenses, you can read half the diameter and then multiply by 2.

TRANSFER TUBE. When you use a measuring magnifier, the reticle must be in contact with the work or an image of the work. Sometimes this is not physically possible, in which case you can "get in" with a transfer tube, Fig. 3. The focal length of negative lenses can be determined with this useful accessory.

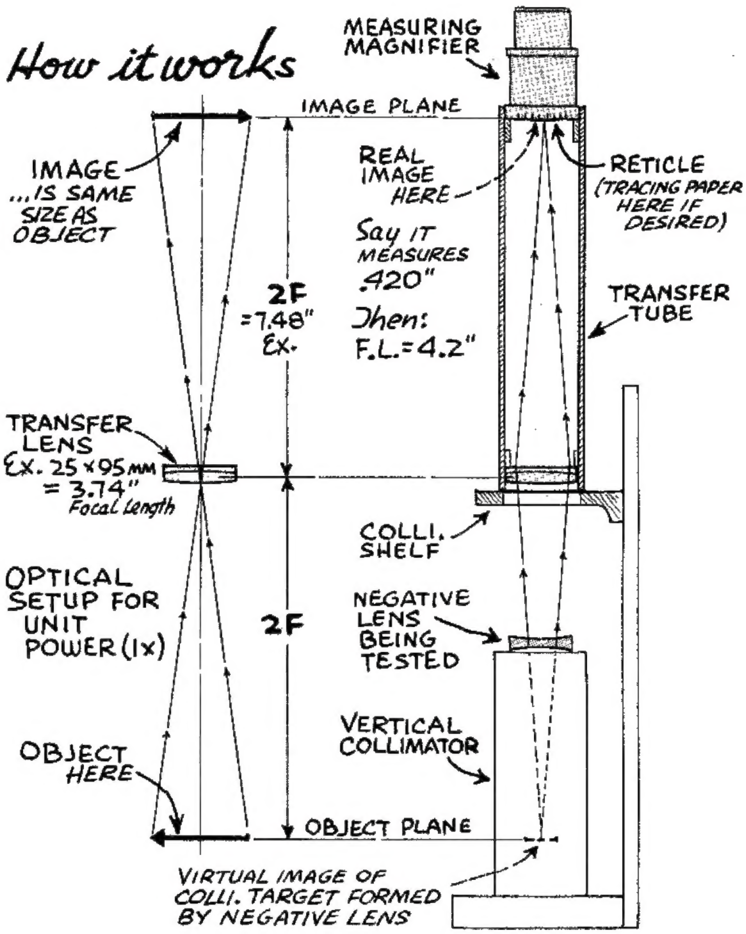
A suitable transfer lens is 25 x 95 mm., as shown in Fig. 3. In its tube it forms a close-range telescope. Such an instrument has an exit pupil, and, because the object (the transfer lens) is relatively close, the eye relief will be long. It is about 1-1/2 inches for the example shown. Other transfer lenses can be used, keeping in mind: a reduction of f.l. will increase the eye relief, and this in turn will reduce the field, possibly to the extent of cutting off the ends of the reticle scale.

Make sure the transfer tube is in proper adjustment by measuring any small target, using a tracing paper screen if desired to assure yourself there is no parallax. The disk of tracing paper can be attached to the magnifier reticle with a few dabs of rubber cement. The whole idea, of course, is that the image must be exactly the same size as the target object. This is controlled by the space between the lens and the magnifier--once you get it right the adjustment is permanent.

A negative lens is measured for f.l. in the same manner as a positive lens, the only difference being the image transfer. The transfer tube is placed on the collimator shelf over the hole. The measuring magnifier is seated at the opposite end of the transfer tube, with or without a tracing paper screen. Then, as before, you rack the shelf up and down until the collimator target is seen sharply in focus. As before, a reading of the target image diameter will reveal the focal length of the lens being tested. You can test lenses to a little less than



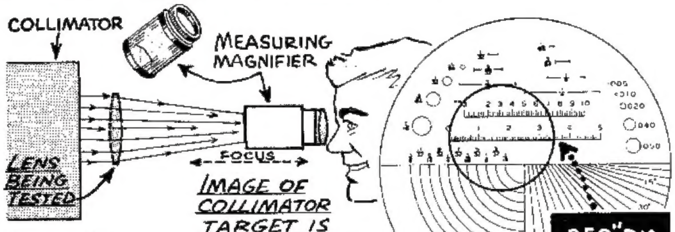
③
UNIT-POWER TRANSFER TUBE



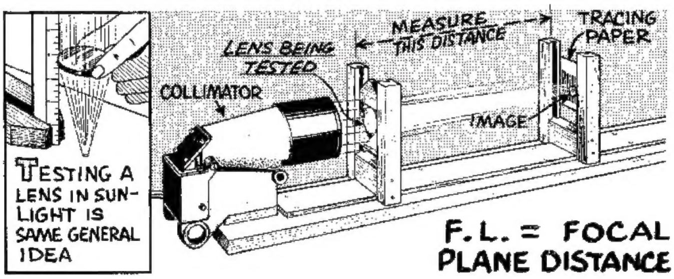
two focal lengths of the transfer lens used, i. e., about 7 in. for the example shown. Longer negative lenses will rack the shelf into the collimator stage. Outward rack movement is needed for very short f.l. negative lenses, the range being to near zero.

For both positive and negative lenses, the "focal collimator" method with 1/10 radian target as just described is the fastest and most convenient way to determine focal length. It is especially good for short f.l. lenses, either singly or in lens systems, such as eyepieces. The accuracy is good, with errors no greater than 2 or 3 percent of the focal length. Try it with a few lenses or eyepieces of known focal length to convince yourself--compare with other methods shown on the following pages.

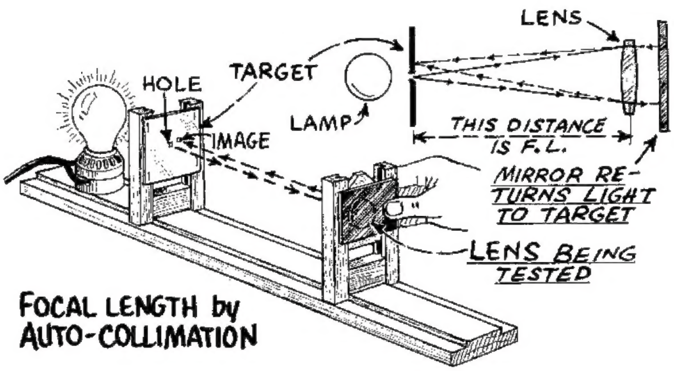
FINDING THE FOCAL LENGTH



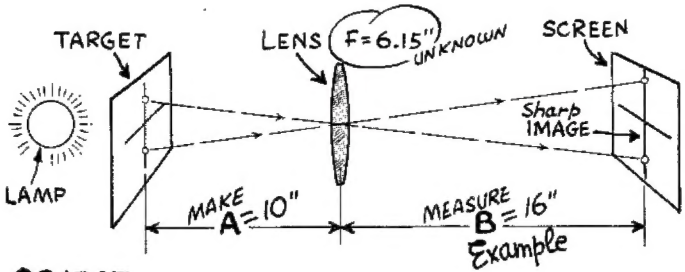
F.L. BY MEASURING IMAGE DIA.



F.L. = FOCAL PLANE DISTANCE

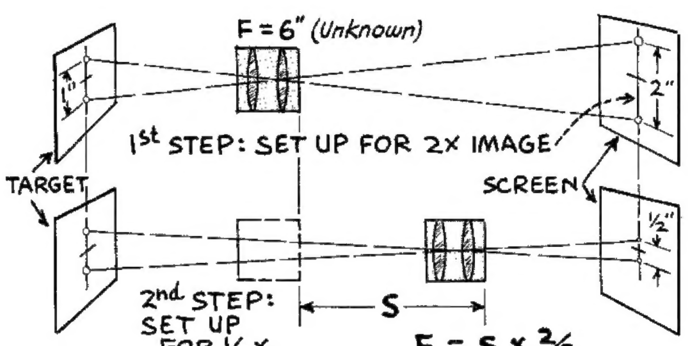


FOCAL LENGTH by AUTO-COLLIMATION



OBJECT-IMAGE CALCULATION

$$F = \frac{A \times B}{A + B} = \frac{10 \times 16}{10+16} = \frac{160}{26} = 6.15''$$



$$F = S \times \tfrac{2}{3}$$

F.L. From LENS MOVEMENT

$$\text{Ex. } F = 9 \times \tfrac{2}{3} = \tfrac{18}{3} = 6''$$

POSITIVE LENSES

FOCAL LENGTH BY IMAGE DIAMETER. This is the collimator and measuring magnifier method described on previous pages. When the collimator constant is made 10, then the f.l. of any lens being tested is 10 times the image diameter. Other collimator constants are sometimes used. In any case, the collimator constant is equal to the f.l. of collimator lens divided by the diameter of the collimator target. Example: If your collimator lens is 8-1/2 inches f.l. and you make the target 1/2 inch diameter, the collimator constant will be 8.5 divided by .5, is 17. It is apparent the odd number multiplier is less convenient than 10.

F. L. FROM FOCAL PLANE DISTANCE. Well-known is the sunlight test, where you focus the sun's image to the smallest possible size. Then, the distance from the image to the lens is the f.l. of the lens. Indoors, you get parallel light like sunlight from a collimator, and the test proceeds as usual. Tracing paper makes a good receiving screen. The f.l. measurement is made (approximately) from the screen to the center of the lens thickness. If the lens is over 1-1/2 in. diameter, it is best to stop it down a bit with a metal washer or cardboard ring to obtain a sharper image.

AUTO-COLLIMATION. This term is used to describe any optical system where light is directed through the system and then returned by the same path. It has many applications. In the setup shown, the target is an opaque material in which is cut a small hole. The target also serves as a screen and should be white on the side facing away from the light. An ordinary flat mirror is held behind the lens being tested. When the lens is the proper distance from the target, it will form a sharp image of the target hole on the target itself, as shown. This method is useful for setting or checking the position of a collimator target, which must be exactly one f.l. from the lens.

OBJECT-IMAGE CALCULATION. There are numerous ways of finding the focal length of a lens from other data which is known or can be determined. One basic method is the relation between object distance and image distance. In making this setup on the lens bench, it is convenient to make the image distance 10 inches, using a "setting stick" if you do the operation frequently. The image is then found by trial and the image distance from lens is measured. The simple formula will then reveal the focal length. It can be seen the figure 10 for object distance simplifies the math work a little.

F. L. FROM LENS MOVEMENT. This method makes use of the relation between projection magnification and focal length. The target is a piece of opaque cardboard with two small holes spaced 1 inch apart, as shown. The eyepiece or lens to be tested is moved along the bench to form a 2x image, that is, the image of the holes will be sharp and 2 inches apart. Then, marking the lens position and leaving both target and image screens in same position, you move the lens toward the screen to form a 1/2x image, as shown in second step. The simple formula then reveals the focal length.

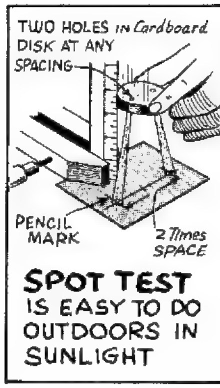
NEGATIVE LENSES

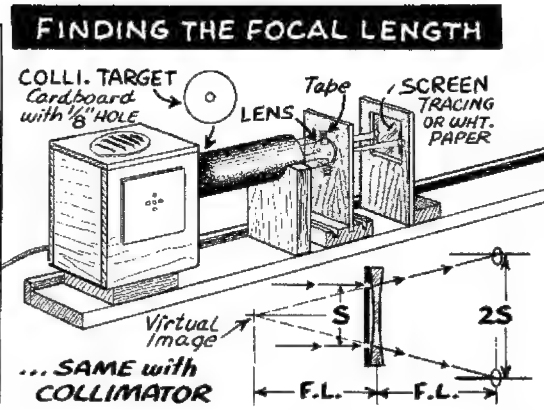
SPOT TEST. A negative lens does not produce a real image. However, the light (sunlight or parallel light from a collimator) can be passed through two small (1/16") round or square holes cut in a cardboard disk which is placed over the lens. You move the disk closer or farther from the screen to make the projected spots appear exactly twice as far apart as their spacing on the cardboard disk. When this has been done, the distance from lens to screen is the focal length of the negative lens. If you test with a collimator, the light should be at least 25-watt.

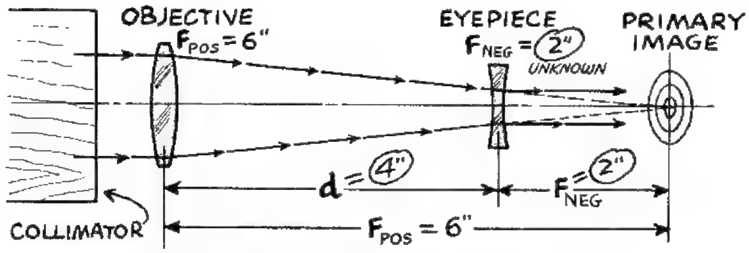
GALILEAN TELESCOPE. The spacing between lenses of a Galilean telescope in focus is equal to the f.l. of the first lens (the objective), minus the f.l. of the second lens (the eyepiece). Knowing this little bit of optical know-how, you can set up a telescope on the optical bench and so determine the f.l. of the negative lens eyepiece. An auxiliary telescope (see page 22) will give you an exact focus independent of any refractive error in your eyes.

2x BARLOW SETUP. Most telescope nuts understand the optics of the Barlow lens, as used to increase the power of a telescope. If you set up for 2x Barlow magnification, the distance from the negative lens to the final image is the same as the f.l. of the negative lens. Make the setup on the optical bench with collimator, as shown. By adjusting the negative lens and screen to form an exact 2x image, you know the distance from screen to lens is the f.l. of the negative lens.

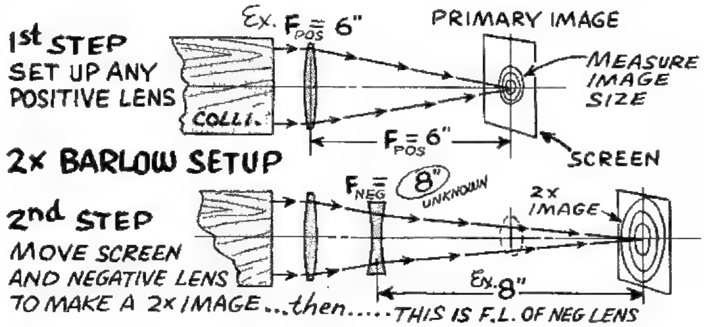
DUPLET CALCULATION. Second only to the measuring magnifier with transfer lens, the direct calculation of negative lens f.l. in a duplet is perhaps the most useful. What you do here is combine a positive lens of known focal length with a negative lens of unknown focal length, the combination being positive, capable of forming a real image. You will know you have a positive combination if it functions as a simple magnifier--if not, use a positive lens of shorter focal length. The e.f.l. of the combination can be determined by any method used to find the f.l. of a positive lens. Knowing the e.f.l. of the combination and the f.l. of the positive lens, it is easy to calculate the f.l. of the negative element.

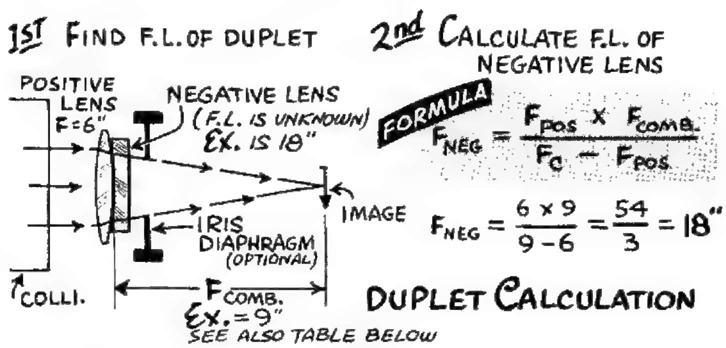






GALILEAN TELESCOPE $(F_{NEG} = F_{POS} - d)$





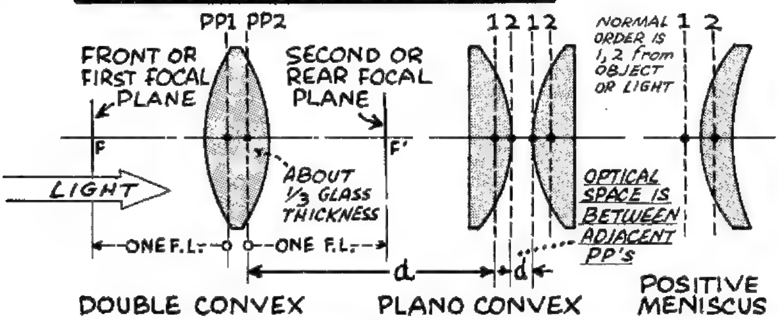
RANGE OF POS-NEG DUPLETS with LENSES IN CONTACT

F.L. RATIO* POS to NEG or NEG to POS		INCREASE IN F.L. OVER POS LENS ALONE	Example LENSES POS-NEG	E.F.L.
4%	25 Times	1.04x	6" and 150"	6.25"
10%	10 Times	1.11x	6" and 60"	6.66"
$12\frac{1}{2}$%	8 Times	1.14x	6" and 48"	6.86"
16½%	6 Times	1.20x	6" and 36"	7.20"
25%	4 Times	1.33x	6" and 24"	8.00"
33%	3 Times	1.5x	6" and 18"	9"
50%	2 Times	2x	6" and 12"	12"

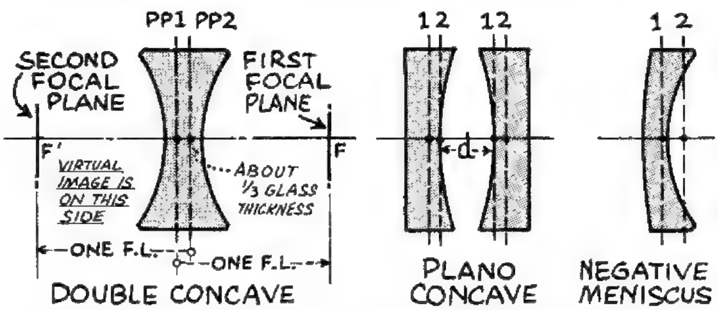
F.L. RATIO* POS to NEG or NEG to POS		INCREASE IN F.L. OVER POS LENS ALONE	Example LENSES POS-NEG	E.F.L.
57%	1¾ Times	2.33x	6" and 10.5"	14"
60%	1⅔ Times	2.5x	6" and 10"	15"
67%	1½ Times	3x	6" and 9"	18"
75%	1⅓ Times	4x	6" and 8"	24"
80%	1¼ Times	5x	6" and $7\frac{1}{2}$"	30"
89%	1⅛ Times	9x	6" and $6\frac{3}{4}$"	54"
100%	1 Time	∞ INFINITE LIKE 1000x	6" and 6"+	∞ LIKE 6000"

* THE F.L. OF POSITIVE LENS MUST BE LESS THAN F.L. OF NEG. LENS TO MAKE A POSITIVE COMBINATION

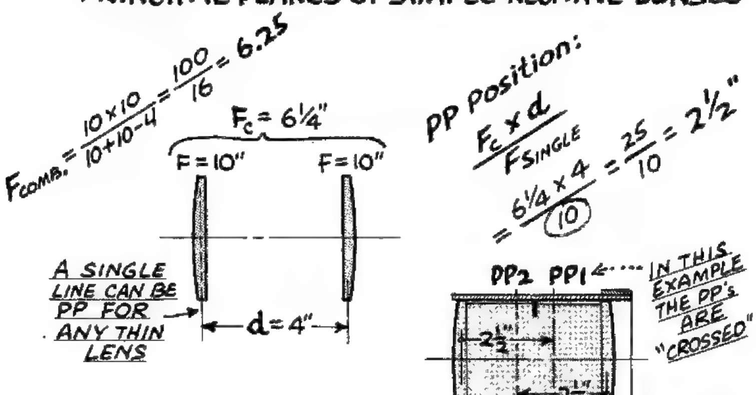
FINDING THE FOCAL LENGTH



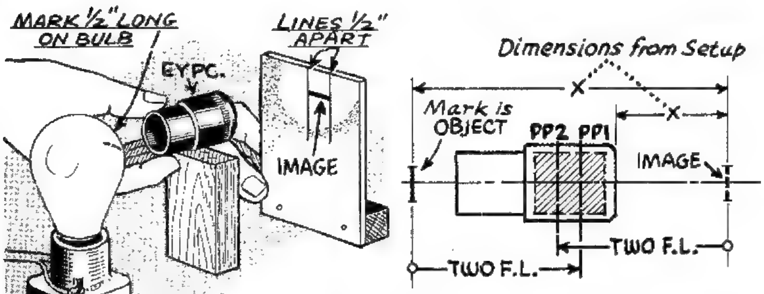
PRINCIPAL PLANES of SIMPLE POSITIVE LENSES



PRINCIPAL PLANES of SIMPLE NEGATIVE LENSES



CALCULATING THE PP's OF A LENS SYSTEM



PP's by 1x MAGNIFICATION

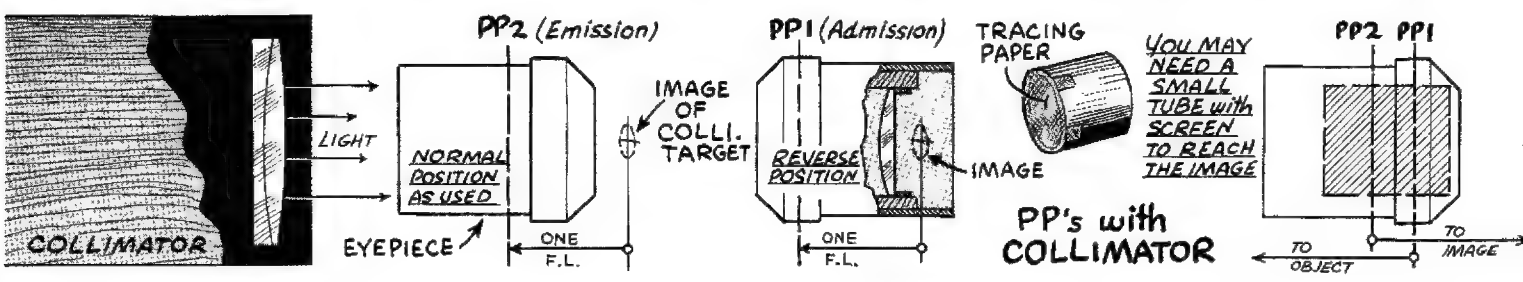
PRINCIPAL PLANES

KNOWING the f.l. of a lens is often incomplete data because you do not know from what part of the lens or lens system the focal length is measured. The two principal planes of a lens are imaginary planes from which the focal length is measured. PP1 is associated with the object side of the lens or any measurement in the object space, while PP2 refers to the image side. The PP's of simple lenses can be located close enough by eye, as shown in the diagrams. Most useful is the fact that one of the principal planes of a plano-convex lens is always at the vertex of the curved surface; this is true regardless of type of glass or glass thickness. Most simple lenses are so thin that one "principal plane" at the center of the glass thickness is accurate enough for most measurements.

CALCULATING THE PP's. If you are making up any two-lens combination or duplet, the PP's of the combined lenses can be easily calculated. When both lenses are identical, the PP's will be symmetrical, as in the example shown. See also page 33. The PP's of a duplet are usually "crossed" as shown. If you are drawing light rays, you go from the object to PP1, then parallel with axis to PP2 (backtracking) and then from PP2 to the corresponding part of the image. The general idea is that you treat the combined lenses as one thick lens with two measuring planes. If the lens system is an eyepiece used as an eyepiece, the object viewed is the image formed by the objective. This is located at one f.l. from PP1.

PP's BY 1x MAGNIFICATION. Usually you will know the f.l. of an eyepiece or other lens system, but the PP's will be unknown. They are easily located with a bench setup similar to the drawing. The general idea is to juggle the eyepiece and screen back and forth until the image on screen is in sharp focus and exactly the same size as the target. This is 1x spacing, indicating the PP's are located two focal lengths from the object and image. The lens bench data is transferred to a full-size outline diagram of the eyepiece. If desired, the PP's can be marked lightly with a scriber on the eyepiece itself

PP's WITH COLLIMATOR. If you put an eyepiece in front of a collimator, the eyepiece will form an image of the collimator target at exactly one focal length of the eyepiece. So, if you measure back one f.l. from the image you will locate PP2, as in first diagram below. Turning the eyepiece around will locate PP1 in the same manner. This may be complicated by the fact the image plane is inside the lens barrel; the use of a tracing paper screen on a short tube will let you reach in to the image.



PP's with COLLIMATOR

CONVEX and CONCAVE MIRRORS

FOCAL PLANE DISTANCE. Like a positive lens, a positive mirror forms an image of a distant object at one focal length. You can use a real object if desired, providing it is truly "distant" (at least 50 f.l.). More often, a collimator provides the distant target. The receiving screen for the image can be a piece of thin white cardboard taped or tacked to the front of the collimator. It can cover part of the lens. You move the mirror back and forth to get the sharpest possible image, using a magnifying glass if needed. Then, the distance from mirror to image is the focal length.

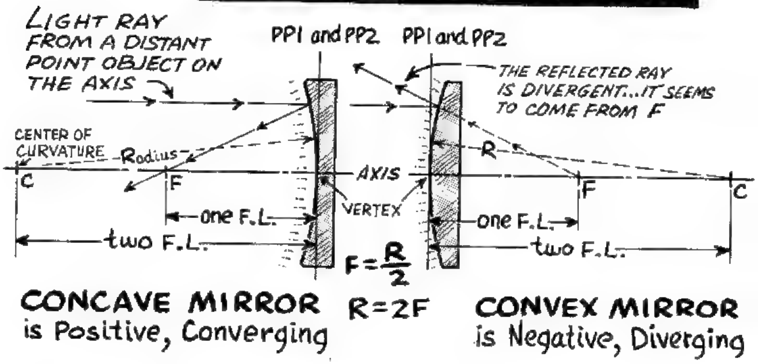
IMAGE DIAMETER. If you are using a 1/10 radian circle as a collimator target, the diameter of the target image will be 1/10 of the focal length. Since most mirrors are rather long f.l., the image can be measured with an ordinary ruler, as shown.

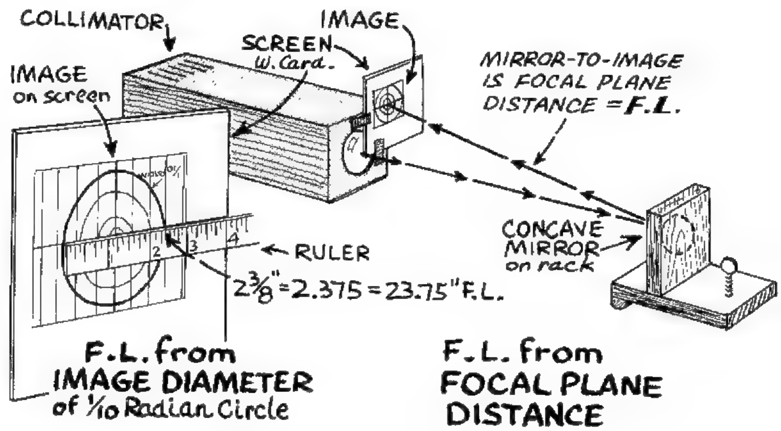
CLOSE TARGET. The receiving screen can be either tracing or white paper; it should be in the same plane as the target. In the setup shown, you move the screen for sharpest image. Then, the distance from screen to mirror is exactly TWO focal lengths.

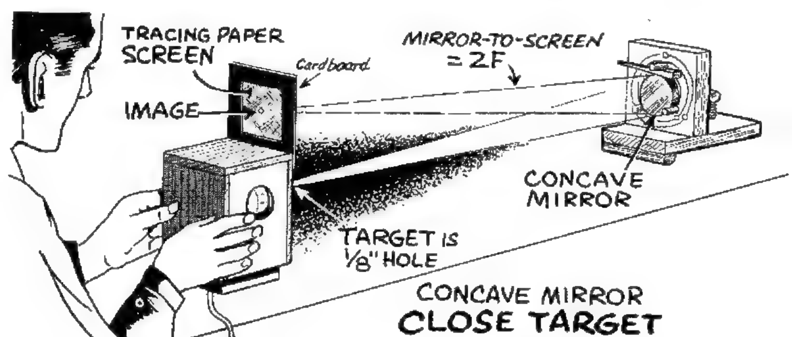
THICK MIRROR. One common way to find the f.l. of a negative mirror is to combine it with a positive lens to make a positive combination. The positive combo can be tested like any positive mirror. After you get f.l. of the combination, the f.l. of the mirror is easily calculated.

RADIUS OF CURVATURE. First, set up any positive lens to make an image of a close target at some considerable distance, as shown in diagram at bottom right. Then, without moving the lens or screen, locate the mirror in such a position as to form an image of the target on the target itself, as shown. Measure from mirror to original lens image to get mirror radius.

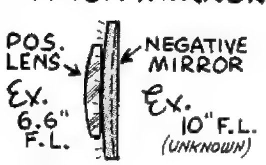
FINDING THE FOCAL LENGTH





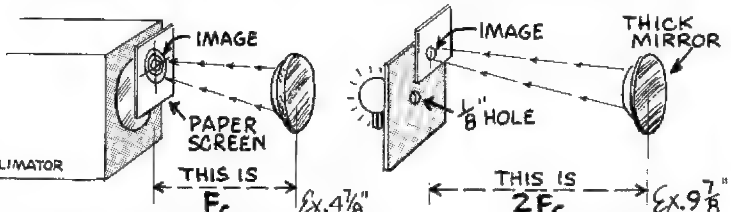


"CONVEX MIRROR "THICK MIRROR" IS A COMBINATION OF LENS AND MIRROR. THE F.L. OF POSITIVE LENS IS KNOWN; F.L. OF MIRROR IS NOT



THE LENS MUST HAVE THE SHORTER F.L. OF THE PAIR TO MAKE A POSITIVE COMB. CAPABLE OF FORMING A REAL IMAGE

First: FIND F_c (F.L. OF THE COMBINATION)



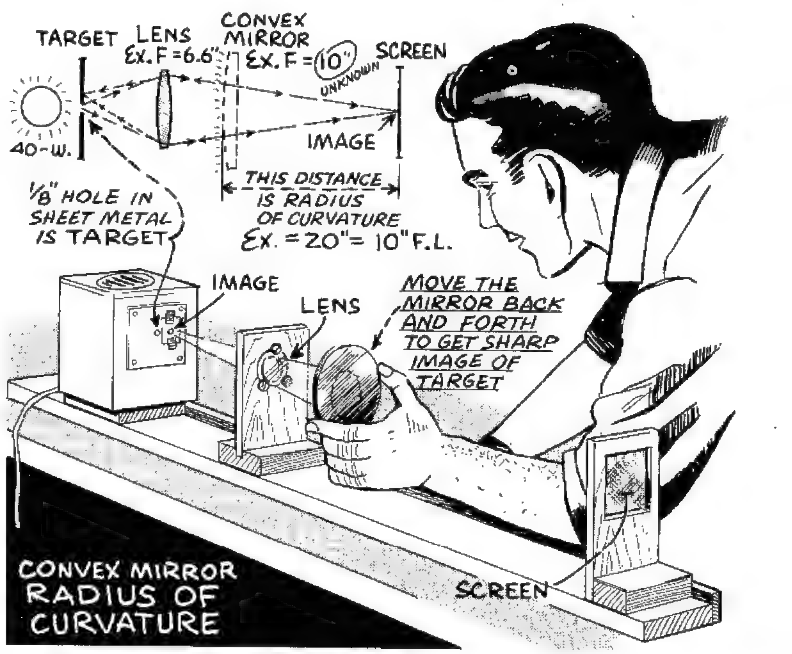
Use COLLIMATOR SETUP...*or*... CLOSE TARGET

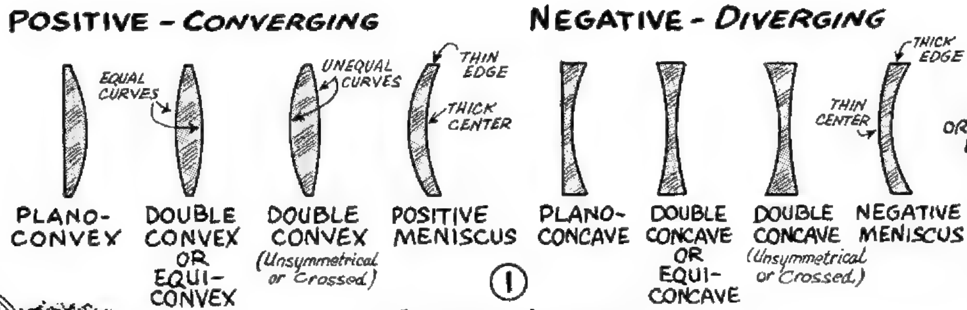
Then:

$$F_{MIR} = \frac{\frac{1}{2}F_{LENS} \times F_c}{F_c - \frac{1}{2}F_{LENS}}$$

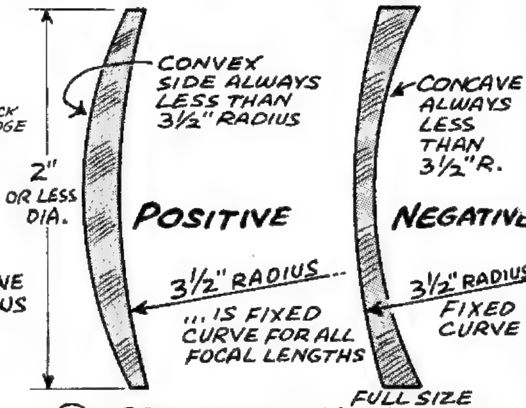
Ex:

$$\frac{3.3 \times 4.9}{4.9 - 3.3} = \frac{16.17}{1.6} = 10''_{NEG.}$$

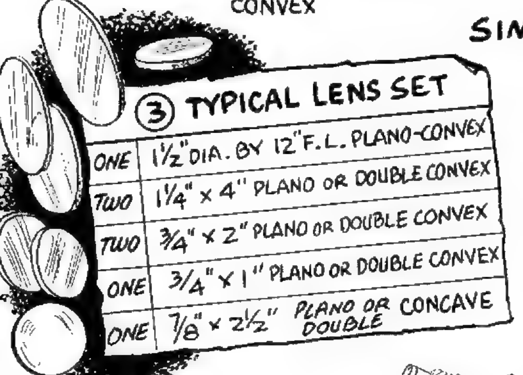




① SIMPLE LENSES



② SPECTACLE MENISCUS

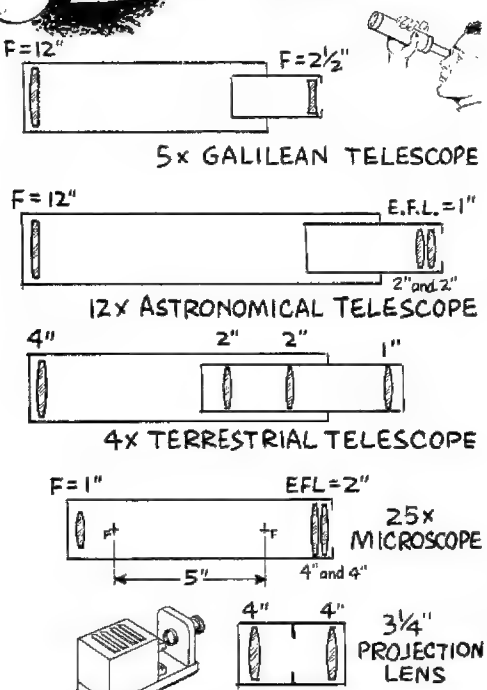


The LENSES You Use

YOU CAN do most optical experiments and build working models of common optical instruments with a "set" of 6 to 10 lenses. Most of the lenses are converging or positive; all are simple lenses made of a single piece of glass. The focal lengths are non-critical--you need a long focal length for a telescope objective, but "long" can be anything from 8 inches to 60 inches. A typical 7-lens demonstration set is shown in Fig. 3, and diagrams, Fig. 4, show instruments you can make with these or similar lenses.

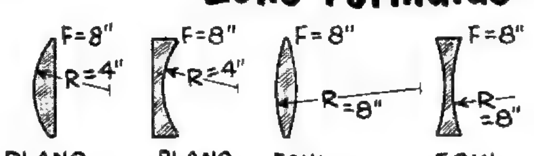
SPECTACLE LENSES. The lenses used for eyeglasses are readily available and are quite satisfactory for experiments and instrument use. The lenses are commonly meniscus shape with one standard surface of fixed curvature, usually 3-1/2 in. radius. The f.l. range in inches is from 2 in. to 320 inches. Supplementary close-up lenses used in photography are similar but usually with a longer standard curve of about 5 in. radius. Nos. 1 through 6 diopters are commonly available; shorter focal lengths are usually double convex shape.

THE DIOPTER SYSTEM. Spectacle and close-up lenses have the f.l. measured in diopters rather than linear inches or millimeters. This is a "power" system, that is, a lens is rated by its refractive power instead of its focal length. The power of a lens is the reciprocal of its focal length. Assume you have a lens of 20 in. focal length. The reciprocal of this is 1/20, which is .05, the power of the lens. When the focal length is given in inches, the power rating has



④ THINGS YOU CAN MAKE

SIMPLIFIED Lens Formulas*



PLANO-CONVEX OR PLANO-CONCAVE

$$F = 2R \qquad R = \frac{F}{2}$$

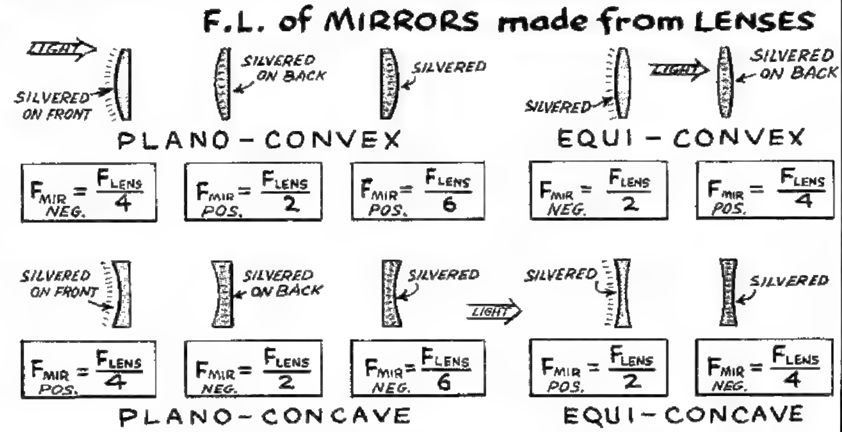
Ex. $F = 2 \times 4 = 8"$, $R = 8/2 = 4"$

EQUI-CONVEX OR EQUI-CONCAVE

$$F = R \qquad R = F$$

Ex. $F = 8"$, $R = 8"$

F.L. of MIRRORS made from LENSES



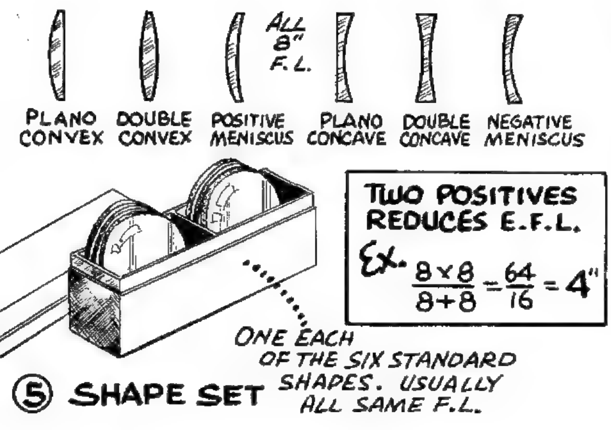
PLANO-CONVEX: $F_{MIR} = \frac{F_{LENS}}{4}$ (NEG.); $F_{MIR} = \frac{F_{LENS}}{2}$ (POS.); $F_{MIR} = \frac{F_{LENS}}{6}$ (POS.)

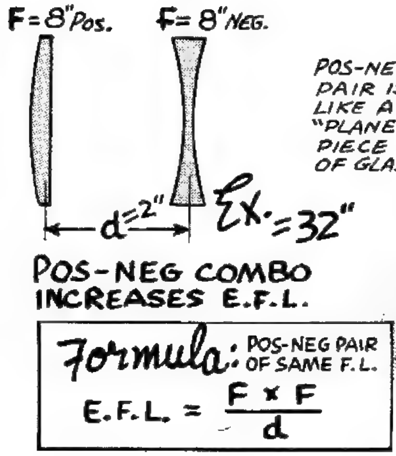
EQUI-CONVEX: $F_{MIR} = \frac{F_{LENS}}{2}$ (NEG.); $F_{MIR} = \frac{F_{LENS}}{4}$ (POS.)

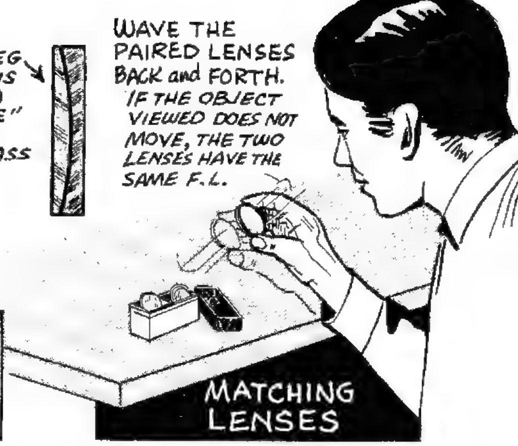
PLANO-CONCAVE: $F_{MIR} = \frac{F_{LENS}}{4}$ (POS.); $F_{MIR} = \frac{F_{LENS}}{2}$ (NEG.); $F_{MIR} = \frac{F_{LENS}}{6}$ (NEG.)

EQUI-CONCAVE: $F_{MIR} = \frac{F_{LENS}}{2}$ (POS.); $F_{MIR} = \frac{F_{LENS}}{4}$ (NEG.)

*APPROXIMATE. EXACT FOR THIN LENSES with 1.50 INDEX. NOT MUCH OFF FOR ORDINARY WHITE CROWN, INDEX 1.52







no particular name, but if the focal length is given in meters, then, the power unit is the Diopter. Since one meter is approximately 40 inches long, the same 20 in. f.l. lens mentioned has a focal length of half a meter, which in decimal notation is .5 meter. If you write this as a reciprocal, you get 1/.5, which is 2, which is specifically 2 diopters, the power of the lens. The Plus 1, Plus 2, etc. designation used for close-up lenses indicate the diopter power although this fact is rarely mentioned. The "Plus," of course, means a positive lens. The common set of supplementary close-up lenses consisting of Nos. 1, 2, 3 and 4 quickly get more understandable labels of 40, 20, 13 and 10 inches focal length. Spectacle and similar meniscus lenses have a f.l. tolerance of 1/16 diopter. This is a tight tolerance for lenses above 10D., but it becomes generous with low D. numbers, being about 1/2 inch for 2D and over an inch for 1 diopter. Hence, the approximate inch equivalent of the dioptric power is used for most applications and calculations, since the exact conversion would be voided by the tolerance.

SHAPE SET. A "shape" set of demonstration lenses contains one each of the six standard shapes, Fig. 5. Usually the lenses are all of the same f.l. This allows you to match a positive with a negative, an operation sometimes useful in actual work when you do not know the f.l. of a negative lens. Looking through the combined lenses held in contact, you know you have a match if the object viewed looks same size and does not move.

You might think the "all same focal length" shape set does not contain the desirable long and short focal lengths needed to demonstrate instruments. However, you can easily put two lenses together, and with various spacings, obtain a variety of focal lengths. Well-known is the fact that two positive lenses of the same focal length will produce a combo with half the f.l. of a single lens. Less known is the fact that a pos-neg combination will have an e.f.l. greater than a single lens. A pos-neg system of this kind is also a telephoto or Barlow case (see Case 5, page 35) and can be calculated for focal length and magnification by the various Case 5 equations.

SMALL MIRRORS. One way of obtaining small positive or negative mirrors is to buy simple lenses of suitable focal length and have them silvered on first or second surface as desired.

DIOPTERS = Millimeters = Inches

D.	MM	INCH APPROX.	INCH EXACT	D.	MM	INCH APPROX.	INCH EXACT	D.	MM	INCH APPROX.	INCH EXACT	D.	MM	INCH APPROX.	INCH EXACT
.25	4000	160	157.48	2.25	444	18	17.48	4.50	222	9	8.74	10	100	4	3.94
.50	2000	80	78.74	2.50	400	16	15.75	5.00	200	8	7.87	11	91	3½	3.58
.75	1333	53	52.48	2.75	364	14	14.33	5.50	182	7	7.17	12	83	3¼	3.27
1.00	1000	40	39.37	3.00	333	13	13.11	6.00	167	6½	6.57	13	77	3	3.03
1.25	800	32	31.50	3.25	308	12	12.13	6.50	154	6	6.06	14	71	2¾	2.80
1.50	667	26	26.26	3.50	286	11	11.26	7	143	5½	5.63	16	63	2½	2.48
1.75	571	22	22.48	3.75	267	10½	10.51	8	125	5	4.92	18	56	2¼	2.20
2.00	500	20	19.69	4.00	250	10	9.84	9	111	4½	4.37	20	50	2	1.97

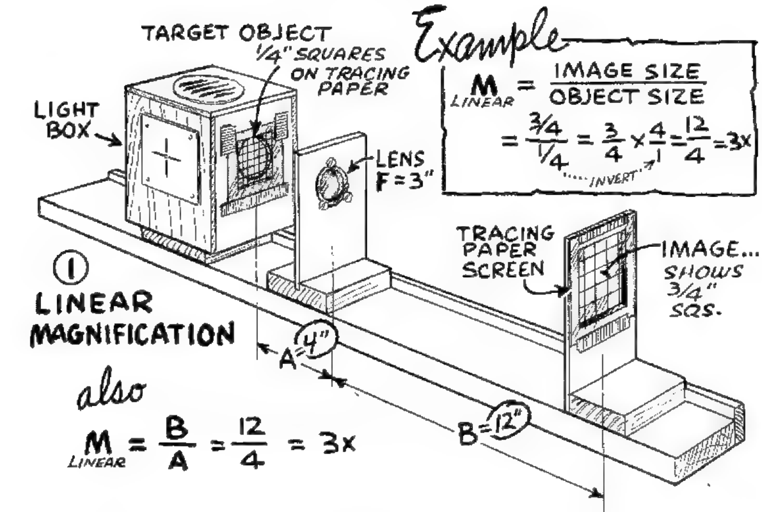
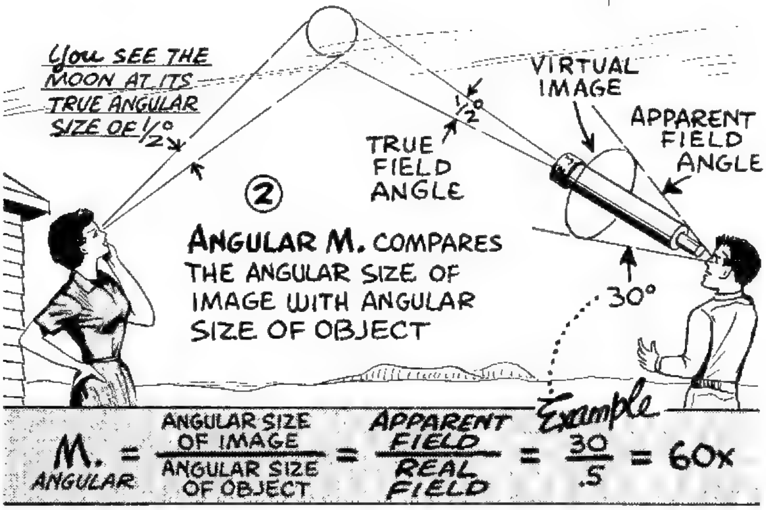
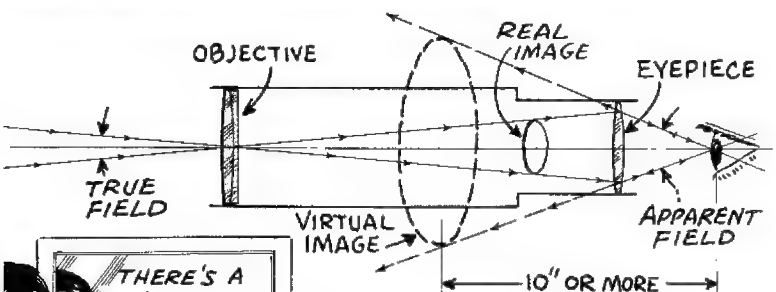


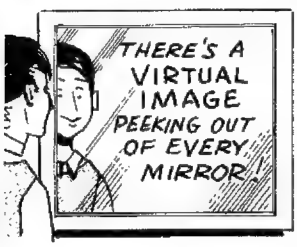
IMAGE Formation

A CLOSE target for use on the lens bench can consist of a tracing paper grid taped over a hole in a plywood lighthouse, as shown in Fig. 1. The grid of lines should be some convenient size--1/4 or 1/2-inch. The image formed by the lens can be picked up on another piece of tracing paper. If you measure the size of the grid squares on the image, you can find the linear magnification. Linear magnification compares the physical size of the image with the physical size of the object.



ANGULAR MAGNIFICATION. Angular M. is a comparison of angles, as can be seen in Fig. 2. It is the kind of magnification used to specify all see-through optical instruments, such as telescopes and microscopes. The final image you see is virtual, that is, the image seems to exist because you can see it, but it is not a real image you can capture on a tracing paper screen or on film. A positive lens used as a simple magnifier is the commonest example of a virtual image formed by an optical instrument. In a telescope, there is a real image in the focal plane of the objective, but the eyepiece views this as a simple magnifier, making the final image a virtual one. In optical theory, you should see a virtual image at infinity, but the actual distance is usually 10 to 40-inches.





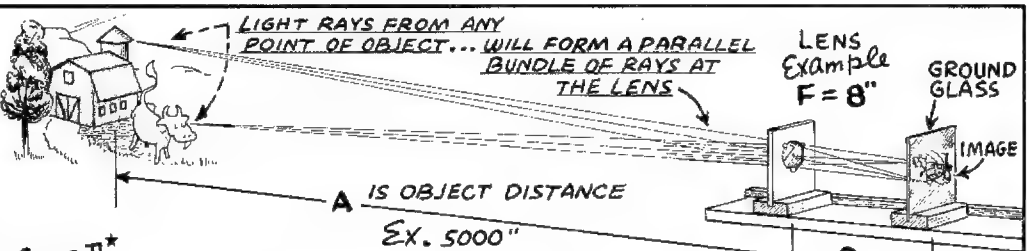
3

HOW A TELESCOPE OR MICROSCOPE FORMS A VIRTUAL IMAGE

BENCH SETUPS WITH A SINGLE LENS. The most common object-image situation is the single positive lens with the object at some distance more than one f.l. but less than infinity. This is a Case 1 situation. Fig. 4 is a diagram

OPTICAL Infinity

Optical infinity can be a greater or less distance depending on how you want to use it. 300 focal lengths is usually long enough. If in doubt, make the calculation shown to determine if the image distance is over one f.l. by an excessive amount.



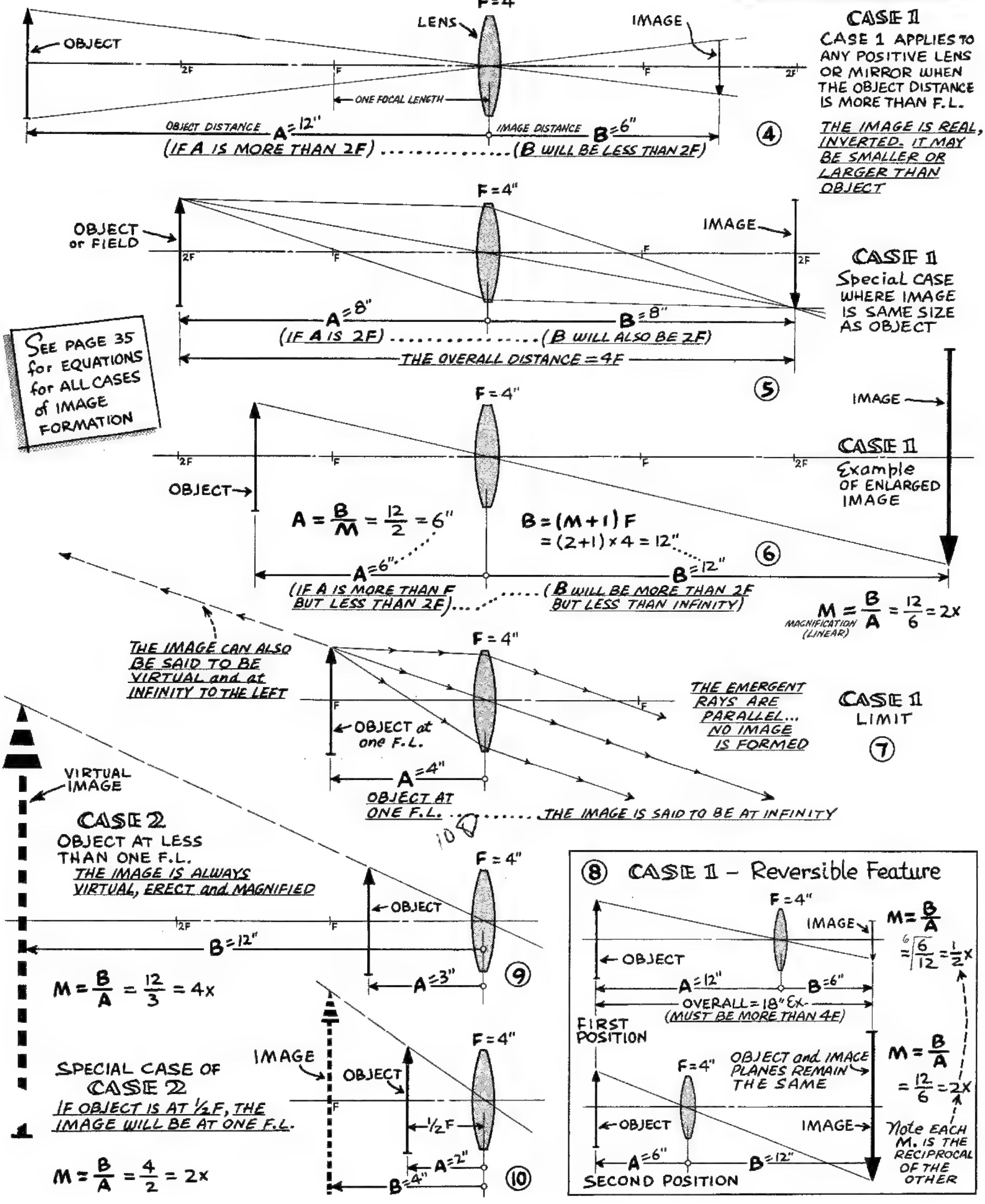
Case II*

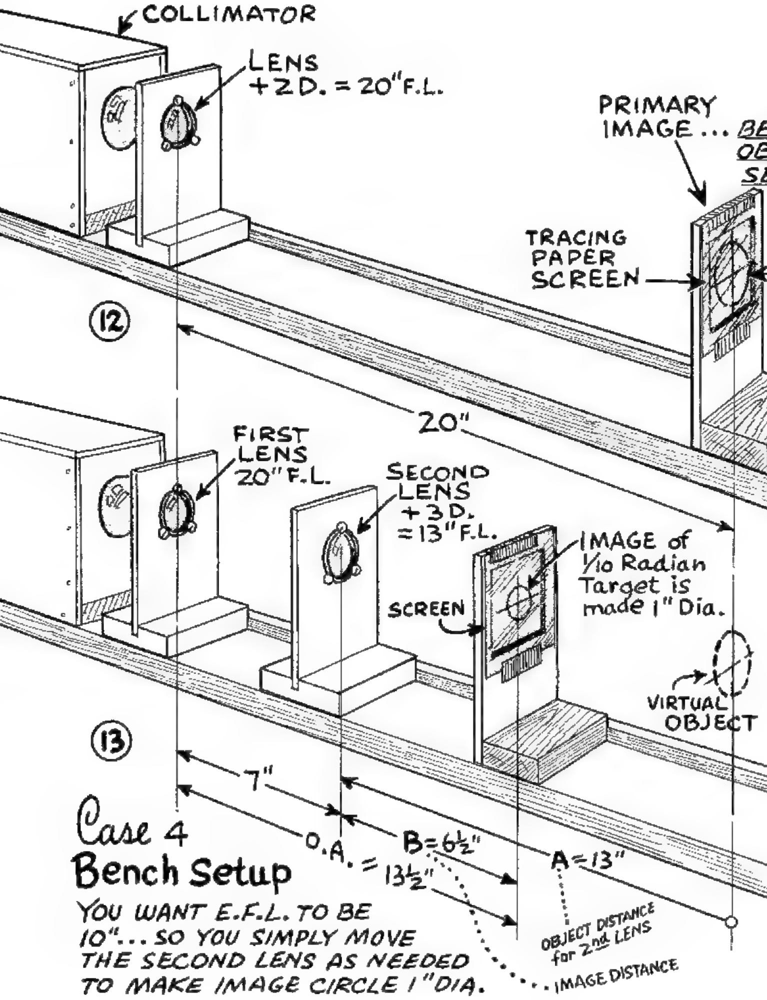
NO.2 $B = \frac{F \times A}{A - F} = \frac{8 \times 5000}{5000 - 8} = \frac{40000}{4992} = 8.01"$

NO.7 $M_{(LINEAR)} = \frac{B}{A} = \frac{8.01}{5000} = .001x$

Calculations CAN BE MADE (AS SHOWN) BUT USUALLY MEAN NOTHING
Practically: FOR OBJECT AT INFINITY $B = F$, $M = ZERO$

* THE VARIOUS OBJECT-IMAGE EQUATIONS ARE GIVEN ON PAGE 35


F=4"
LENS
IMAGE
OBJECT
2F
F
F
2F
ONE FOCAL LENGTH
OBJECT DISTANCE A=12"
IMAGE DISTANCE B=6"
(IF A IS MORE THAN 2F) .... (B WILL BE LESS THAN 2F)
4
CASE 1
CASE 1 APPLIES TO ANY POSITIVE LENS OR MIRROR WHEN THE OBJECT DISTANCE IS MORE THAN F.L.
THE IMAGE IS REAL, INVERTED. IT MAY BE SMALLER OR LARGER THAN OBJECT
F=4"
OBJECT or FIELD
IMAGE
2F
F
F
2F
A=8"
B=8"
(IF A IS 2F) .... (B WILL ALSO BE 2F)
THE OVERALL DISTANCE = 4F
5
CASE 1
Special CASE WHERE IMAGE IS SAME SIZE AS OBJECT
See PAGE 35 for EQUATIONS for ALL CASES of IMAGE FORMATION
F=4"
IMAGE
2F
F
F
2F
OBJECT
CASE 1
Example OF ENLARGED IMAGE
A = B/M = 12/2 = 6"
B = (M+1) F
= (2+1) × 4 = 12"
6
A=6"
B=12"
(IF A IS MORE THAN F BUT LESS THAN 2F) ..... (B WILL BE MORE THAN 2F BUT LESS THAN INFINITY)
M = B/A = 12/6 = 2X
MAGNIFICATION (LINEAR)
THE IMAGE CAN ALSO BE SAID TO BE VIRTUAL and at INFINITY TO THE LEFT
F=4"
F
F
OBJECT at one F.L.
THE EMERGENT RAYS ARE PARALLEL... NO IMAGE IS FORMED
CASE 1
LIMIT
7
A=4"
OBJECT AT ONE F.L. .... THE IMAGE IS SAID TO BE AT INFINITY
VIRTUAL IMAGE
CASE 2
OBJECT AT LESS THAN ONE F.L.
THE IMAGE IS ALWAYS VIRTUAL, ERECT and MAGNIFIED
F=4"
OBJECT
2F
F
B=12"
A=3"
9
M = B/A = 12/3 = 4x
F=4"
IMAGE
OBJECT
SPECIAL CASE OF CASE 2
IF OBJECT IS AT ½F, THE IMAGE WILL BE AT ONE F.L.
F
½F
A=2"
B=4"
10
M = B/A = 4/2 = 2x
8 CASE 1 – Reversible Feature
F=4"
IMAGE
M = B/A
= 6/12 = ½X
OBJECT
A=12"
B=6"
OVERALL = 18" Ex.
(MUST BE MORE THAN 4F)
FIRST POSITION
F=4"
OBJECT and IMAGE PLANES REMAIN THE SAME
M = B/A
= 12/6 = 2X
OBJECT
IMAGE
A=6"
B=12"
SECOND POSITION
Note EACH M. IS THE RECIPROCAL OF THE OTHER



CASE 4

MATH Solution (11)

Example:*

F.L. of FIRST LENS = 20" (2 DIOPTERS)
F.L. of SECOND LENS = 13" (3 Diop.)
DESIRED E.F.L. of COMBO = 10"
Required M. of Second Lens = $\frac{10}{20} = \frac{1}{2}$x

CASE 4 NO. 5: $A = \frac{F}{M} - F = \frac{13}{1/2} - 13$ (INVERT) $= 13 \times 2 - 13 = 13"$

CASE 4 NO. 3: $B = A \times M = 13 \times \frac{1}{2} = 6\frac{1}{2}"$

*THIS EXAMPLE IS A SPECIAL CASE OF CASE 4: IF M IS ½x, A WILL BE THE SAME AS F, and B WILL BE ½ F

of a Case 1 setup, with the object more than two focal lengths from the lens. By this condition, the image will be smaller than the object. When the object is exactly two focal lengths from the lens, you get unity magnification or 1x, as shown in Fig. 5. If you push the lens closer to the object, you begin to get actual magnification of the image, as shown in Fig. 6. If you continue to push the lens closer to the object, the image will become larger and larger and will also be a greater and greater distance from the lens, reaching the ultimate limit when the object is at one focal length, Fig. 7. In this situation, and also for the opposite situation where the object is at infinity, the various math formulas become useless for the simple reason "infinity" means any great distance--it is not something you can label for every situation. But if you move the lens a hair in either direction, you have a setup which can be calculated.

An interesting feature of Case 1 is its reversibility. If you make a lens setup like Fig. 4, you can switch to the setup shown in Fig. 6 by merely moving the lens, the object and image remaining in the same position. This feature is shown again in Fig. 8, where it can be seen one position gives less than unity M. while the other position is greater than unity, each being the reciprocal of the other. This is one of the basic systems used in zoom lenses. The whole magnification range from low to high is the square of the high-power magnification. In Fig. 8, the whole M. is 2x times 2x equals 4x--the high-power is four times the low-power.

CASE 2. When the object is closer than one focal length from the lens, you have a Case 2 situation, as shown in Fig. 9. The lens bench will fail you here because the image is virtual; you can see it plain enough but you can't capture the image to locate its exact position. However, the math work for this is quite simple. The common magnifying glass is the best example of Case 2, although the same situation occurs in many other optical systems.

TWO POSITIVE LENSES. A positive lens is a converging lens. When two positive lenses are used, it is apparent that both will act to converge the light rays. The result is a combination of shorter focal length than the longer of the two lenses. Assuming a distance object, the primary image will form at one focal length, Fig. 12. If you are using a 1/10 radian target, the image of this will be exactly 1/10 of the focal length. Now, if you want some shorter f.l. by using a second lens, all you have to do is put the lens in place and move it back and forth until the collimator target image is 1/10 of the desired focal length. In the example, Fig. 13, the combination is made 10 in. e.f.l.

The magnification factor of the second lens is independent of the first lens--you can apply the same setup to any other front lens and it will do its thing in the same manner, the only condition being that the first lens must form

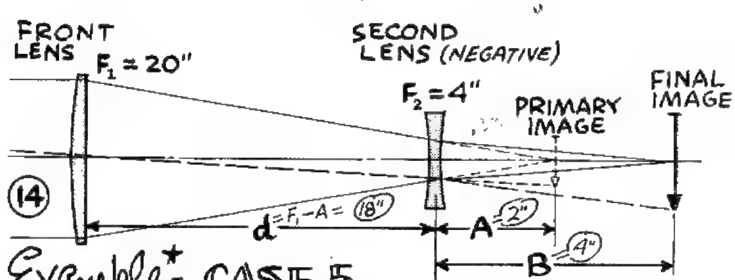
the primary image at the established position. Any magnification factor can be specified, but in no case can you actually increase the magnification, that is, it must always be some M. less than unity, such as 1/2x or 1/3x or 3/4x, etc. The simple calculations are shown in Fig. 11 and may be used to supplement the actual bench setup.

CASE 5, Case 5 concerns the negative lens of a positive-negative combination, the negative lens being the second lens in the system. The negative lens in Case 5 is often called a Barlow lens from its use as an amplifying lens in a telescope system; the second lens in Case 4 is sometimes called a Bertrand lens from its application in a microscope system.

The Barlow lens is an amplifier, the range being from slightly over 1x, up to as high as you care to go. The system is exceptionally compact, as can be seen in Fig. 14 sample where an increase of 2 in. in physical length gives 20 additional inches focal length. Like Case 4, you can check and test most Case 5 setups on the optical bench. Like Case 4, the second lens with its spacing is an independent system which can be used interchangeably with any front lens. Exactly the same equations apply to a similar system done with mirrors; the Cassegrain telescope is a well-known example.

When located about halfway between first lens and final image, the Barlow lens presents the minimum illuminated face to the light cone. This position is sometimes used or favored to minimize the aberrations of a simple lens Barlow. You can easily find the spacing for this condition with a lens bench test, or it can be calculated like Fig. 16 example.

When a Barlow lens is more than one f.l. from the primary image, you have a Case 6 situation. The final image is virtual and to the left. This system is sometimes used for magnifiers.



Example* - CASE 5

specified: M = 2x
F = 4" (NEGATIVE)

CASE 5 NO. 5 $A = F - \frac{F}{M}$

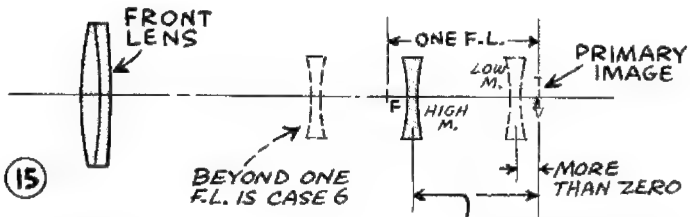
$= 4 - \frac{4}{2} = 4 - 2 = 2''$

CASE 5 NO. 3 $B = A \times M = 2 \times 2 = 4''$

Overall = 18 + 4 = 22"

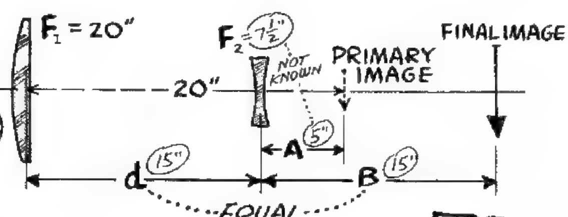
E.F.L. = 20 × 2 = 40"

CASE 5
THE PRIMARY IMAGE IS THE OBJECT FOR THE SECOND LENS
*THIS EXAMPLE (2x) IS A SPECIAL CASE: IF M. IS 2X, B WILL EQUAL F and A WILL BE ½F



CASE 5
LENS POSITION

Example
M = 3x
(M is specified)



CASE 5 SPECIAL FORMULA $A = \frac{F_1}{M+1} = \frac{20}{3+1} = 5''$

CASE 5 NO. 3 $B = A \times M = 5 \times 3 = 15''$

CASE 5 NO. 11 $F_2 = \frac{B}{M-1} = \frac{15}{3-1} = 7\frac{1}{2}''$

Overall Length = 15 + 15 = 30"

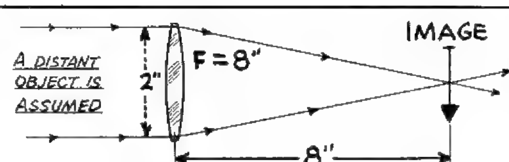
E.F.L. = $F_1 \times M$ = 20 × 3 = 60"

16 Special CASE OF CASE 5
NEG LENS TO BE MIDWAY BETWEEN FIRST LENS AND FINAL IMAGE

f/value of a LENS

The f/value of a lens is the ratio of clear aperture to focal length. It is assumed that the object is fairly distant--at least 30 times the focal length. For close objects, the image distance will exceed f.l. In such case, the effective f/value is based on the image distance.

$$\text{EFFECTIVE f/VALUE} = \frac{\text{IMAGE DISTANCE}}{\text{CLEAR APERTURE}}$$



$$f/\text{VALUE} = \frac{\text{F.L.}}{\text{DIA.}}$$

Example: $f/ = \frac{8}{2} = f/4$

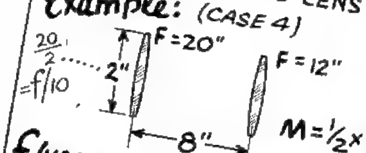
You can transpose:

$$\text{DIA. OF LENS} = \frac{\text{F.L.}}{f/\text{VAL.}} \qquad \text{DIA.} = \frac{8}{4} = 2''$$

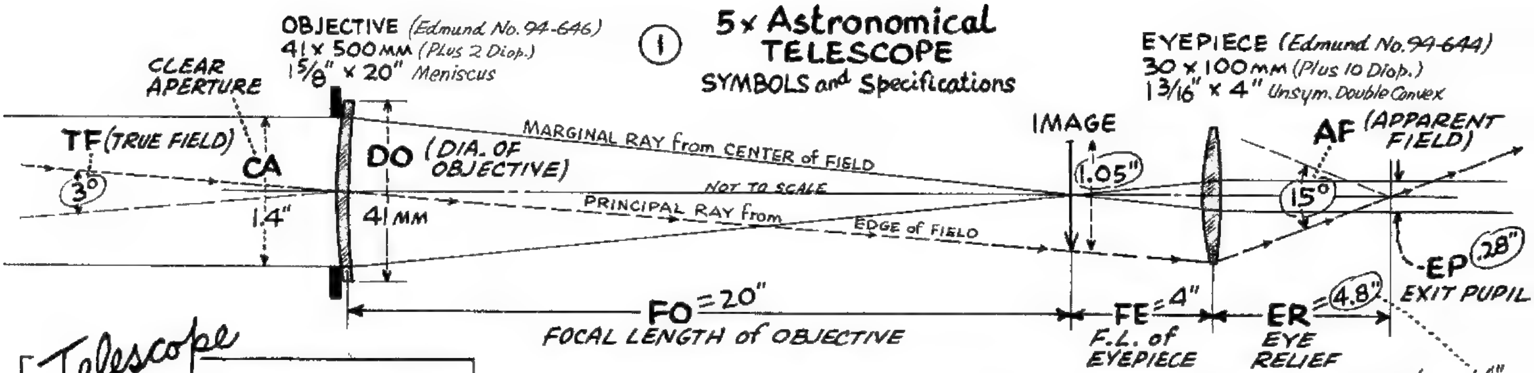
$$\text{F.L. of LENS} = f/\text{VAL.} \times \text{DIA.} \qquad \text{F.L.} = 4 \times 2 = 8''$$

FOR A CASE 4 OR 5 LENS SYSTEM, THE f/VALUE OF THE COMBINATION IS f/VALUE OF FRONT LENS times M. OF SECOND LENS

Example: (CASE 4)



f/VALUE = f/10 × ½ = f/5



DEMONSTRATION Instruments

Telescope ARITHMETIC ②

THREE WAYS TO FIND MAGNIFICATION

	Example
M = FO ÷ FE	$\frac{20}{4} = 5\times$
M = CA ÷ EP	$\frac{1.4}{.28} = 5\times$
M = AF ÷ TF	$\frac{15}{3} = 5\times$

OTHER USEFUL FORMULAS

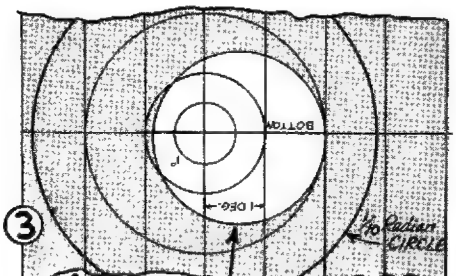
	Ex: above
FO = M × FE	5 × 4 = 20"
FE = FO ÷ M	20 ÷ 5 = 4"
CA = M × EP	5 × .28 = 1.4"
EP = CA ÷ M	1.4 ÷ 5 = .28"
TF = AF ÷ M	15 ÷ 5 = 3°
AF = M × TF	5 × 3 = 15°
IMAGE (DIA.) = TF (in Radians)* × FO	.0524 × 20 = 1.05"

*SEE TABLE AT BOTTOM of OPPOSITE PAGE

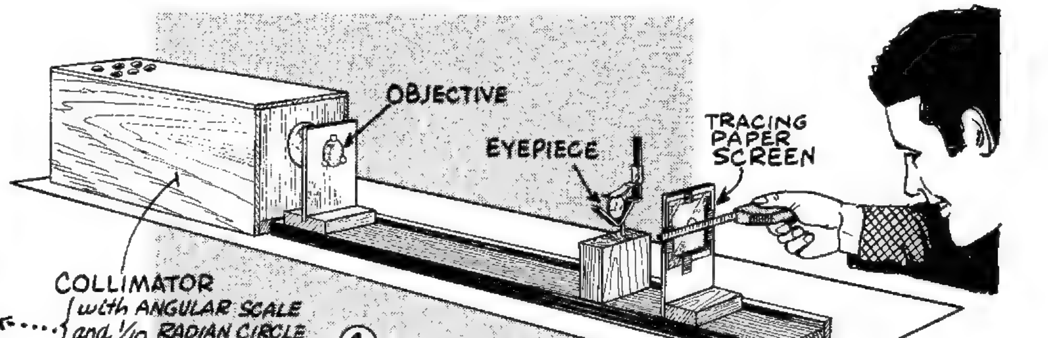
TELESCOPES are ideal instruments for demonstration on the optical bench by using a collimator to supply the needed distant target. For convenience, the collimator target should be an angular scale with 1/10 radian circle, as described on other pages. To determine the true angular field of any telescope, you simply count the degree marks you can see when looking through the instrument, Fig. 3.

The simplest telescope makes use of just two lenses, separated by a distance equal to the sum of their focal lengths. The image forms in the focal plane of the objective and is then viewed by the eyepiece which acts as a simple magnifier.

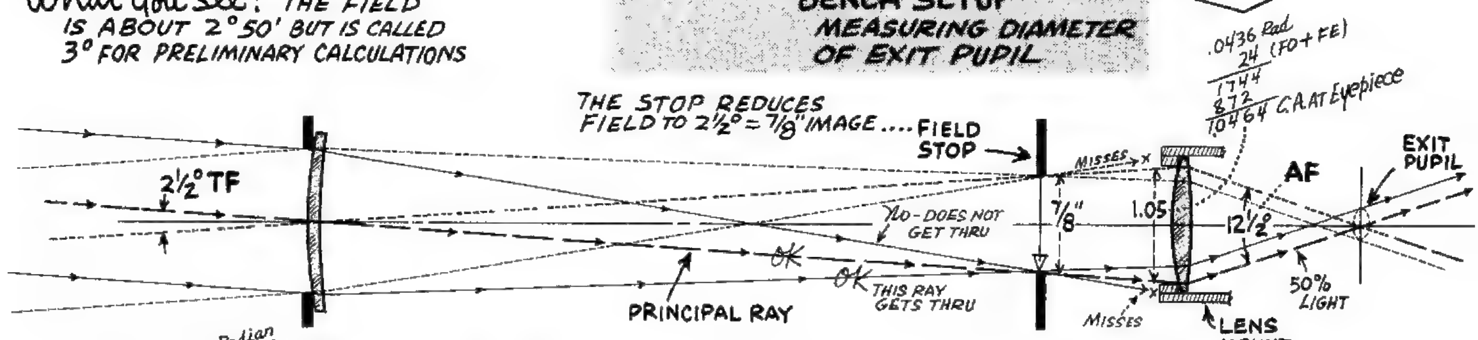
Fig. 1 shows a simple astro telescope, while Fig. 4 shows how it looks on the optical bench. The exit pupil is a picture of the objective formed by the eyepiece; as a calculation it is an easy Case 1 problem. Of course the lens bench allows you to junk all of the



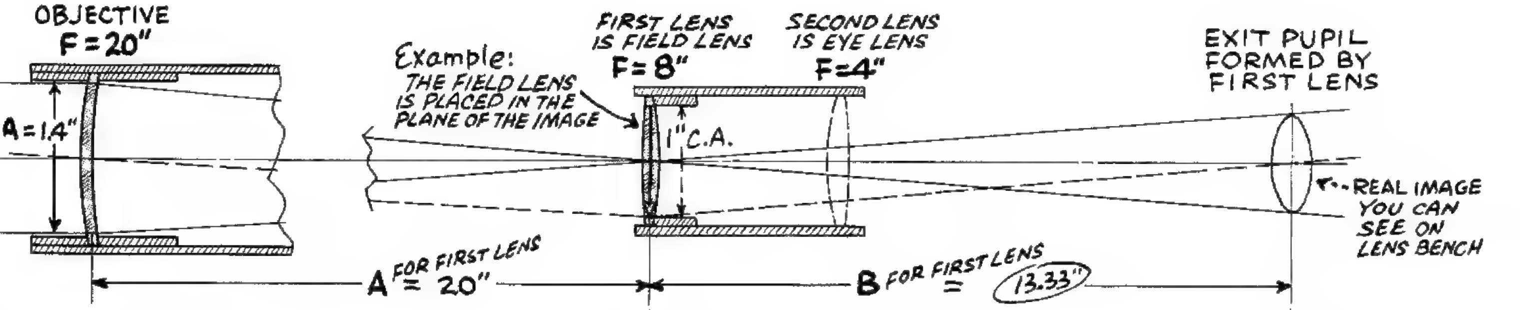
③ What you See: THE FIELD IS ABOUT 2°50' BUT IS CALLED 3° FOR PRELIMINARY CALCULATIONS



④ BENCH SETUP
MEASURING DIAMETER OF EXIT PUPIL



FINAL DESIGN
⑤ 50% LIGHT from EDGE of FIELD is COMMON STANDARD

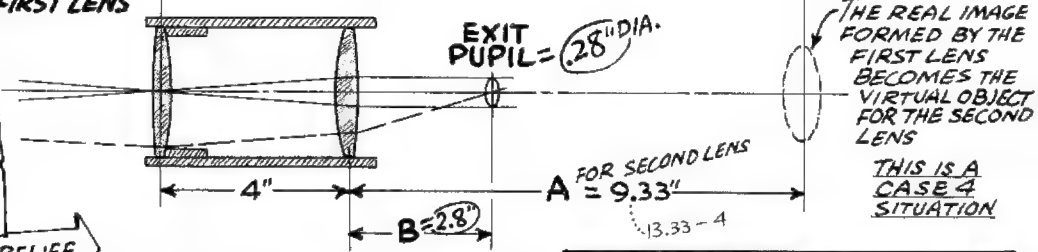


(6) TWO-LENS EYEPIECE--ACTION OF FIRST LENS

FACT: A FIELD LENS AT THE IMAGE PLANE WILL NOT CHANGE THE POWER OF A TELESCOPE

Proof: $\text{E.F.L. EYPC.} = \frac{8 \times 4}{8+4-4} = 4"$ WHICH IS SAME AS EYE LENS ALONE

But NOTE SHORTENING OF EYE RELIEF



(7) ACTION OF SECOND LENS

arithmetic if desired since everything you need to know can be obtained directly from the bench setup.

The final design of the sample instrument, Fig. 5, has the field slightly reduced by a field stop placed at the focal plane. In most telescopes, 50% illumination at edge of field is adequate and standard. You are assured this lighting if you can pass the principal ray (through center of objective) through the instrument. A fullsize scale drawing is probably the best way to visualize the performance of individual light rays. The bench setup is a little weak in this respect since if you get even a glimmer from edge of field, you will probably say the field is fully illuminated. The explanation and reason for 50% lighting at edge of field is that your eyes are self-compensating, being much more sensitive to light in this area.

TWO-LENS EYEPIECE. Put a positive lens of any focal length in the image plane of the sample telescope. You will note it does not change the power of the telescope at all, but it pulls in the exit pupil, Fig. 7. If you remove the eye lens, you can locate the position of the exit pupil formed by the field lens alone, Fig. 6. From this data you can make a complete light ray diagram. If you like, you can also get this data by math, as shown in Fig. 8. Keep in mind you are no longer concerned with a telescope as such, but simply want to find

(8) Math SOLUTION

POSITION and SIZE OF EXIT PUPIL FORMED BY TWO LENSES
(THE OBJECT TO BE IMAGED IS THE C.A. OF OBJECTIVE)

FIRST LENS:

$F = 8"$

$A = 20"$

CASE 1, No. 2: $B = \frac{8 \times 20}{20-8} = 13.33"$

ALL CASES: $M = \frac{B}{A} = \frac{13.33}{20} = .67\times$

SECOND LENS:

$F = 4"$

$A = 9.33"\ (13.33-4)$

CASE 4, No. 2: $B = \frac{4 \times 9.33}{4+9.33} = 2.8"$

$M = \frac{B}{A} = \frac{2.8}{9.33} = .3\times$

WHOLE M = M OF LENS 1 × M of LENS 2 $= .67 \times .3 = .201\times$

EP DIA. $= 1.4 \times .2 = .28"$

TELESCOPE $M = \frac{1.4}{.28} = 5\times$ JUST THE SAME AS EYE LENS ALONE

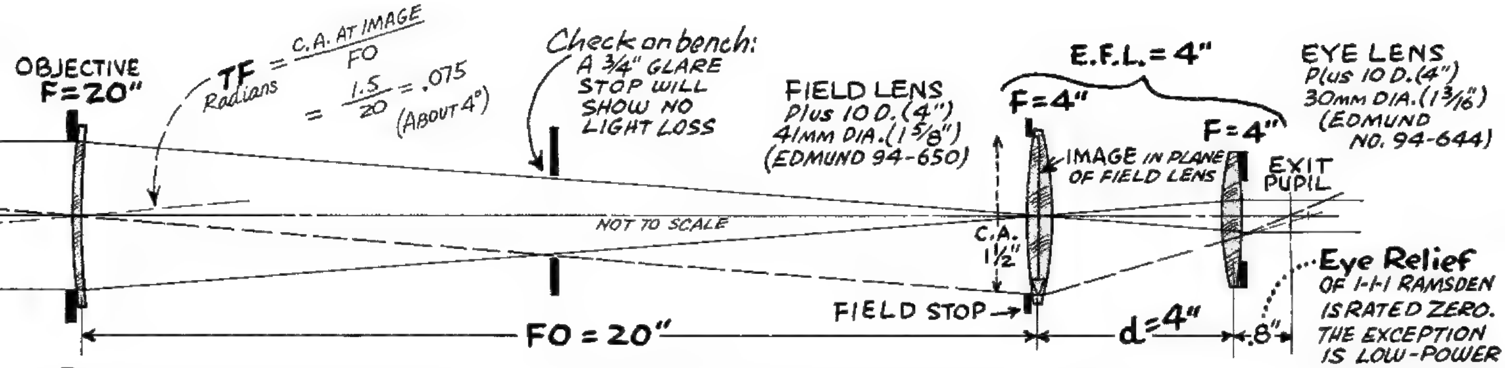
.0049

Conversions

You can ADD values if desired to get DATA for TRUE FIELDS not listed

TRUE FIELD	= Radians	= FT. at 1000 YDS.	TRUE FIELD	= Radians	= FT. at 1000 YDS.	TRUE FIELD	= Radians	= FT. at 1000 YDS.	TRUE FIELD	= Radians	= FT. at 1000 YDS.
1′	.0003	1 FT.	1°	.0175	52 FT.	4°	.0698	210 FT.	9°	.1571	471 472 FT.
10′	.0029	9	1°15′	.0218	65	4°30′	.0785	236	10°	.1745	524 525
15′	.0044	13	1°30′	.0262	79	5°	.0873	262	11°	.1920	576 578
20′	.0058	17	1°45′	.0305	92	5°30′	.0960	288	12°	.2094	628 631
30′	.0087	26	2°	.0349	105	6°	.1047	314	13°	.2269	681 683
40′	.0116	35	2°30′	.0436	131	6°30′	.1134	340	14°	.2443	733 737
45′	.0131	39	3°	.0524	157	7°	.1222	367 367	15°	.2618	785 790
50′	.0145	44	3°30′	.0611	183	8°	.1396	419 420	16°	.2793	838 843

CALCULATED BY RADIANS... ...CALCULATION by TRIG...is more EXACT



⑨ 5x ASTRO TELESCOPE..... with 1-1-1 RAMSDEN EYEPIECE

the image of an object, which in this case is the objective lens of the telescope. Its image is the exit pupil.

RAMSDEN EYEPIECE. This most-common eyepiece consists of two identical plano-convex lenses with curved sides facing. Other lens shapes are quite satisfactory for low-power instruments. On the lens bench, you can make a Ramsden for the sample scope by using another Plus 10 close-up lens as a field lens, Fig. 9. Commonly this is a little larger than the eye lens, as shown, although same-size lenses are favored for simplest construction. As before, with field lens in the plane of the image, there is no change in the power of the telescope. However, you gain field, while the eye relief is a comfortable 3/4 inch. The lens spacing is one-half the sum of the focal lengths of the two lenses, a condition which gives nearly complete correction for lateral color. However, you have some uncorrected lateral color from the simple lens objective, and this is visible, faint but discernible, showing as a fringe around the black lines of the collimator target, blue on one side and red on the other.

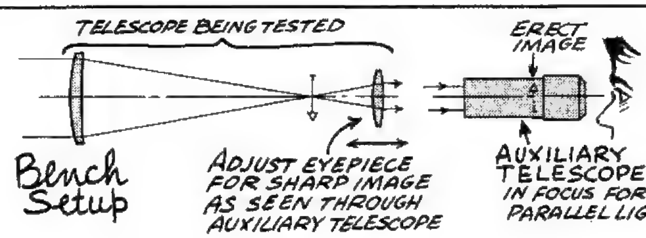
In short focal lengths, the 1-1-1 Ramsden becomes impractical because the eye relief is too short. To gain eye relief, the spacing is decreased to about 2/3 the f.l. of one lens of the pair. Fig. 10 shows a low-power example where the increased eye relief would have no merit. As can be seen, the image moves out in front of the field lens, and the field lens itself is out-of-focus and so does not show dust marks on its surface. The closer lens spacing produces some lateral color but it is not excessive.

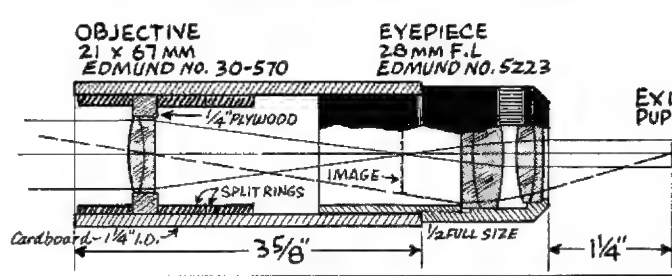
HUYGENS EYEPIECE. Christian Huygens designed the first two-lens eyepiece about 1650. That it is still around and very much in use is proof enough it is a good eyepiece. With lens spacing one-half of the sum of the two lenses, the Huygenian is free of lateral color. Properly designed, it is free of coma. Its weakness is an excessive amount of spherical aberration, nearly five times more than the Ramsden. Since S.A. is compounded by a low f/number, the Huygens is rarely used for f/numbers under f/8. Incidentally, an eyepiece has no f/rating of its own since it always takes on the same value as the objective it is used with.

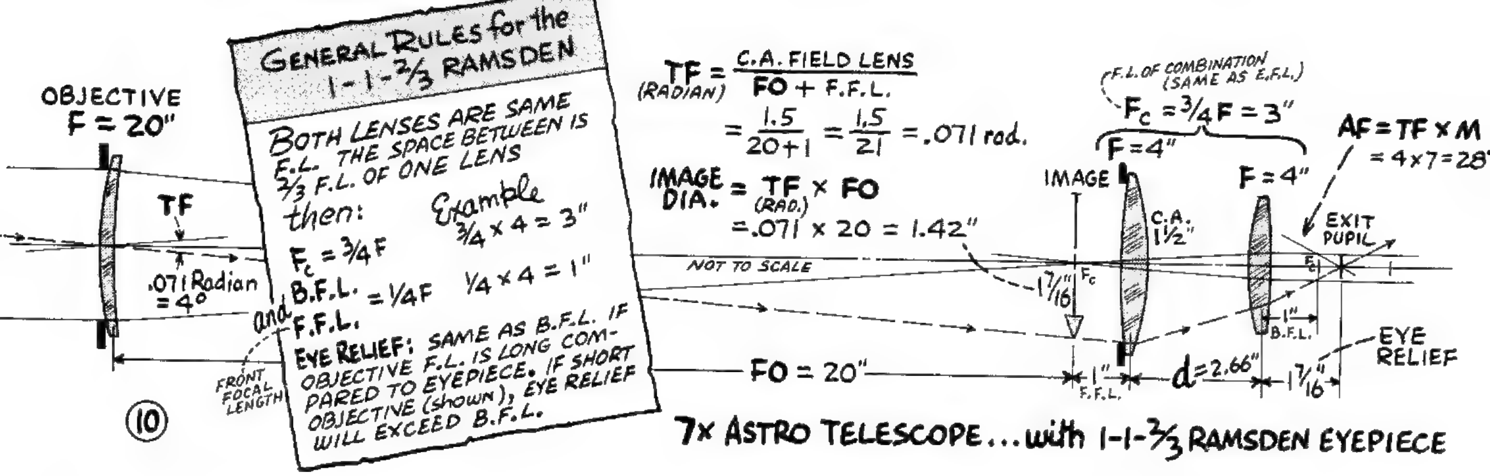
The standard Huygens has a field lens two to three times the focal length of the eye lens, the

2½x Auxiliary Telescope

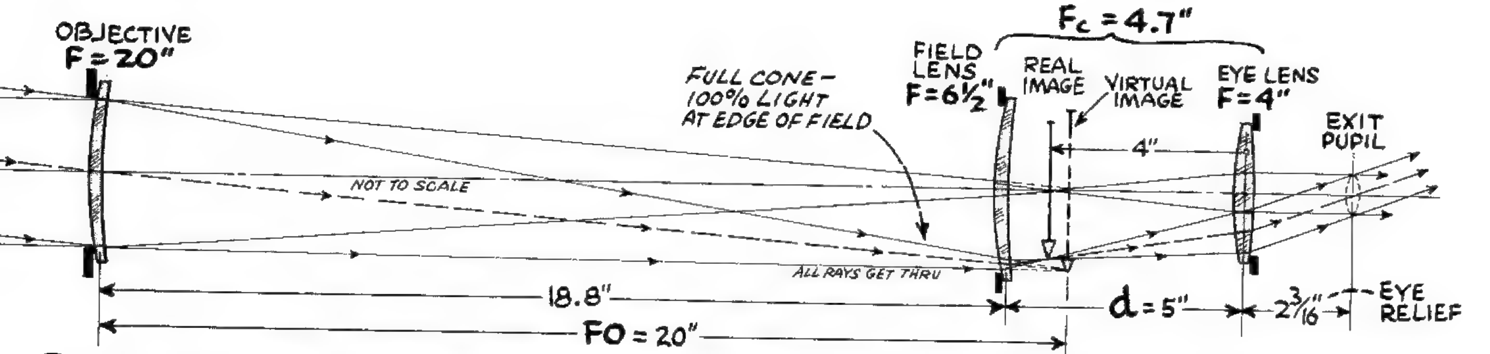
Practically everyone focuses a telescope "in" a little more than needed, making the emergent light divergent instead of parallel. In particular a myope without his glasses may focus "in" as much as an inch from normal. This does not hurt the optical performance, but it does change the lens spacing. One simple solution is the auxiliary telescope. This is focused on a distant target or collimator, and the focus is fixed. When you use the auxiliary behind any other telescope, you are forced to focus the telescope being tested for emergent parallel light because the auxiliary scope is set for that condition.



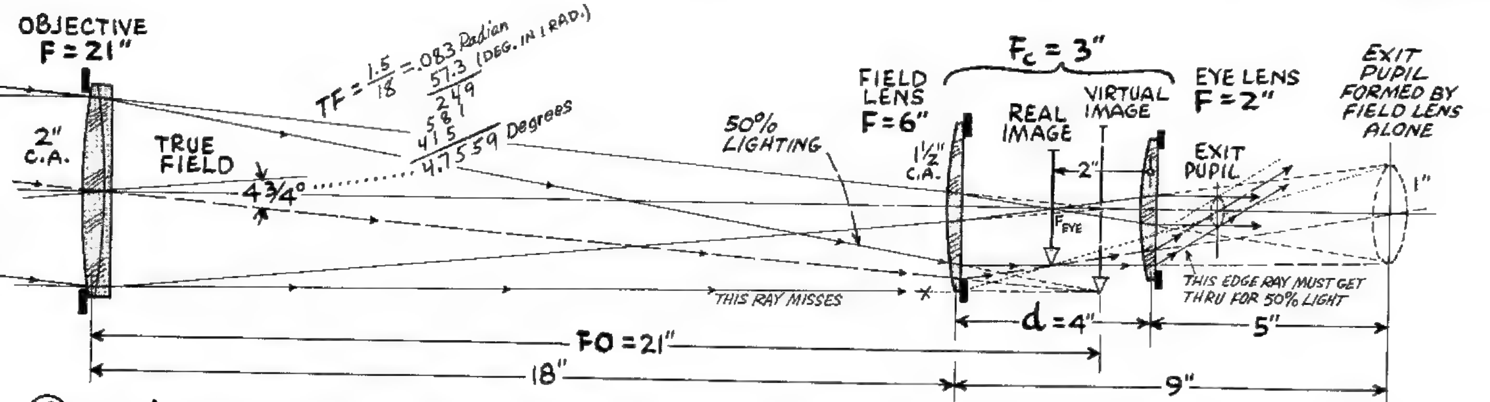




7x ASTRO TELESCOPE...with 1-1-2/3 RAMSDEN EYEPIECE



(11) 4x Demonstration ASTRO TELESCOPE with HUYGENS EYEPIECE, Ratio of 1.6 (F.L. OF FIELD LENS IS 1.6 times F.L. OF EYE LENS)



(12) 7x ASTRO TELESCOPE with 3" F.L. HUYGENS EYEPIECE, Ratio of 3 (NOTE: THIS HIGH RATIO WOULD NOT BE USED FOR A 7X SCOPE)

ratio increasing with the power of the telescope, Fig. 13. This same idea can also be applied to the Ramsden for best coma correction and increased eye relief. Fig. 11 shows a low-power telescope with a Huygens eyepiece of low ratio. As can be seen, the image is between the lenses, which is a unique feature of the Huygens. With a higher ratio, the image moves toward the eye lens, as can be seen in Fig. 12. The final image coincides with the focal plane of the eye lens. From this known fact you can calculate the primary, virtual image plane, using Case 4, No. 6 equation.

GALILEAN TELESCOPE. A Galilean telescope uses a negative lens for an eyepiece, the instrument being somewhat like a long-range

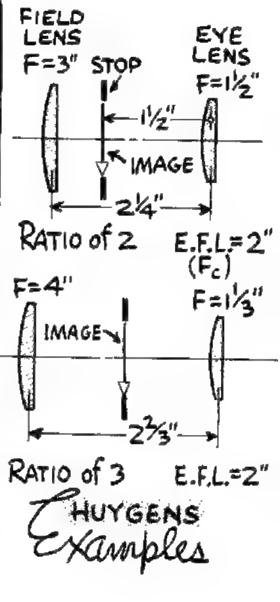
(13) Ratio — F.L. OF FIELD LENS GREATER THAN F.L. OF EYE LENS

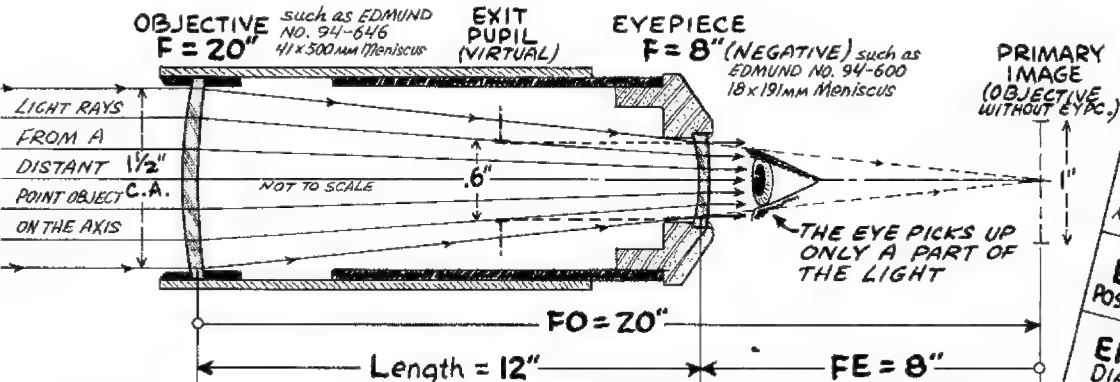
M*	HUYGENS	RAMSDEN
10x OR LESS	1.3 TO 1.6	1 TO 1.1
10x TO 20x	1.5 TO 2	1.1 TO 1.2
20x TO 40x	2 TO 2.6	1.2 TO 1.3
OVER 40x	2.5 TO 3	1.3 TO 1.4

*THE FACTOR ACTUALLY INVOLVED IS THE NUMBER OF FOCAL LENGTHS OF EYEPIECE BETWEEN EYEPIECE AND OBJECTIVE

(14) GENERAL Rules - HUYGENS

	RATIO 2	RATIO 3
F.L. FIELD LENS	$\frac{3}{2}F_c$ OR $2F_{EYE}$	$2F_c$ OR $3F_{EYE}$
F.L. EYE LENS	$\frac{3}{4}F_c$	$\frac{2}{3}F_c$
SPACE (d)	$1\frac{1}{8}F_c$ OR $\frac{3}{2}F_E$	$\frac{4}{3}F_c$ OR $2F_E$
E.F.L. (F_c)	$\frac{4}{3}F_{EYE}$	$\frac{3}{2}F_{EYE}$
STOP POSITION	IN FOCAL PLANE OF EYE LENS	MIDWAY





(15) 2½x GALILEAN TELESCOPE

(17) GALILEAN ARITHMETIC — Example

$M = \frac{FO}{FE}$ — $\frac{20}{8} = 2\frac{1}{2}x$

$AF = \frac{C.A.}{L}$ (Radians) — $\frac{1.5}{12} = .125$ Rad. $= 7.16°$

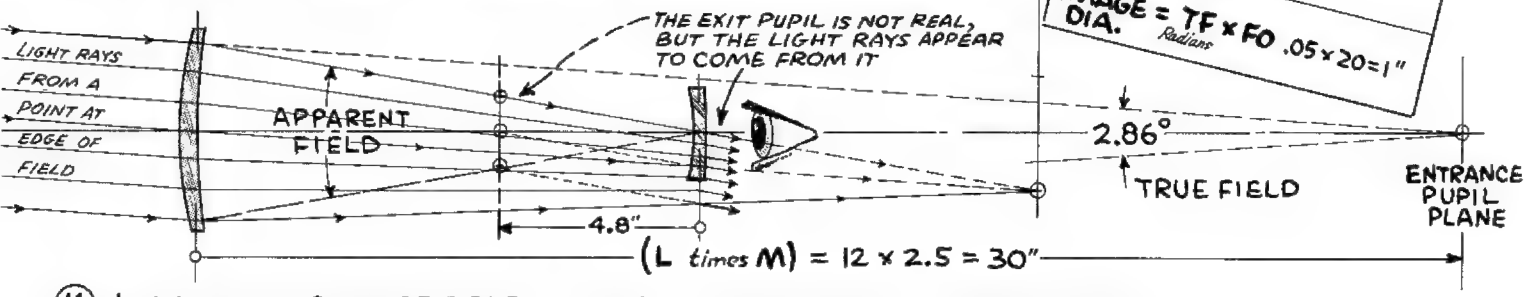
$TF = \frac{C.A.}{L \times M}$ (Radians) — $\frac{1.5}{12 \times 2.5} = .05$ Rad. $= 2.86°$

EP Position $= \frac{L}{M}$ — $\frac{12}{2.5} = 4.8"$

EP Dia. $= \frac{C.A.}{M}$ — $\frac{1.5}{2.5} = .6"$

Pri. Image Dia. $= TF$ (Radians) $\times FO$ — $.05 \times 20 = 1"$

$\frac{.125}{57.3}$ .375 .875 .625 7.1625°



(16) LIGHTING AT EDGE OF FIELD... *ONLY A FEW RAYS GET THROUGH TO EYE*

magnifying glass. The image is erect. The familiar bright spot of the exit pupil behind the eye lens is missing. Instead, the image of the objective formed by the eye lens is a virtual image inside the instrument. This is where you should put your eye, but since this is impossible, all you can do is squeeze your eye close to the eyepiece to capture as much field as possible.

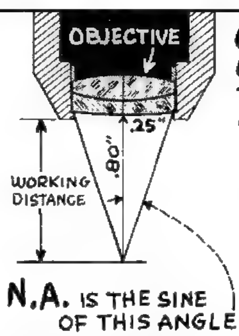
Fig. 15 is a sample Galilean; you can make hundreds of other designs from available lenses. Usually the eyepiece is much shorter f.l. than the sample shown. To obtain maximum field, the objective of a Galilean telescope must have a large diameter compared to its focal length. F/3 achromats are often used for quality instruments. The sample design is about f/13, and so is rather small field from the start. As usual for all telescopes, the true field is the apparent field divided by the magnification. You can easily duplicate Fig. 16 diagram and so determine the apparent and true fields of any design. Technically, the eye itself is the aperture stop for the Galilean, which means the entrance pupil is the image of the eye formed by the objective.

TELEPHOTO LENS. With closer spacing the optical system of the Galilean telescope becomes a telephoto lens. Fig. 18 shows a simple sample. The main feature of any telephoto lens is that its equivalent or effective focal length is greater than its physical length.

This is an easy system to design or set up. For a math solution, it is Case 5--the specific equations you are likely to use are repeated in Fig. 19. It is not necessary to calculate the exit pupil, but this may be done if desired by the

Numerical Aperture

N.A. is to a microscope objective what f/number is to a photo objective. A high N.A. number has the same significance as a low f/number--both indicate a lens with a relative large aperture compared to its focal length. The N.A. numbers are fairly well established in the same manner as f/15 is the standard for refracting telescope objectives, but departures from the standard N.A. numbers listed are common.



N.A. IS THE SINE OF THIS ANGLE

Example:

TANGENT of ANGLE $= \frac{.25}{.80} = .312$

from TRIG TABLE

17°			
MIN.	SINE	COSINE	TANGENT
19	.2976	.9547	.3118
20	.2979	.9546	.3121
21	.2982	.9545	.3124

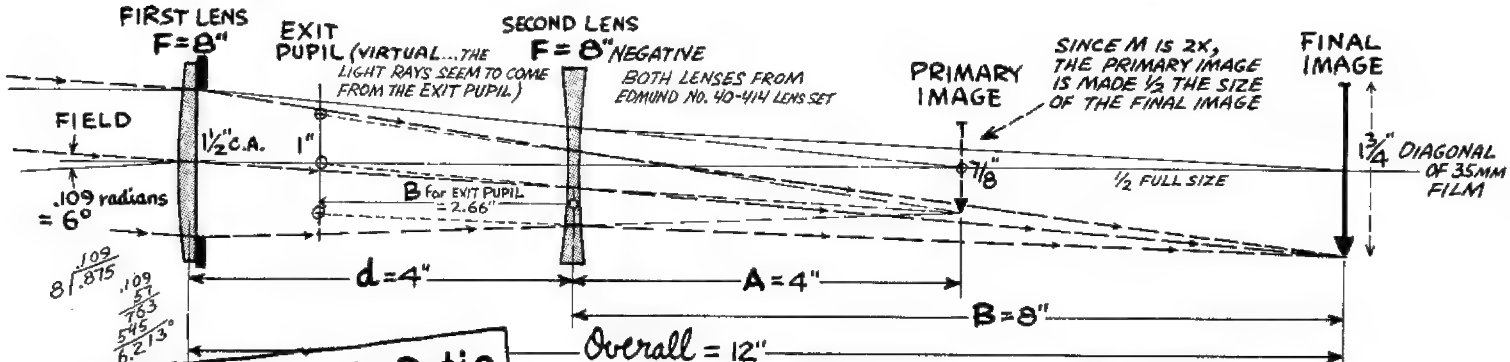
FIRST, CALCULATE THE TANGENT OF THE ANGLE. Then, ANY TRIG TABLE WILL GIVE THE CORRESPONDING SINE

N.A. IS .30

STANDARD OBJECTIVES

F.L. MM.	M.*	N.A.[□]	APPROX. f/
50	3.2x	.08	f/6
32	5x	.10	f/5
25	6.4x	.12	f/4
16	10x	.25	f/2
8	20x	.50	f/1
4	40x	.65	f/0.8

* PRIMARY M... *WITH 160 MM OPTICAL TUBE LENGTH*
□ STANDARD... *BUT OTHER VALUES ALSO USED*



(18) SIMPLE 2x TELEPHOTO LENS ... Ratio 1-1-½

Rules for 1-1-½ Ratio

1. BOTH LENSES SAME F.L.
2. SPACE IS ½ OF ONE LENS
3. E.F.L. IS ALWAYS 2F

then:	Example
E.F.L. = 2F	E.F.L. = 2×8 = 16"
A = ½F	A = ½×8 = 4"
B = F	B = 1×8 = 8"
d = ½F	d = ½×8 = 4"
overall = 1½F	O.A. = 3/2×8 = 12"
or ¾ E.F.L.	OR ¾×16 = 12"

(19) GENERAL RULES for ANY TELEPHOTO OR BARLOW SYSTEM

You SELECT DESIRED M. (USUALLY 2X TO 5X)
then: (CASE 5)

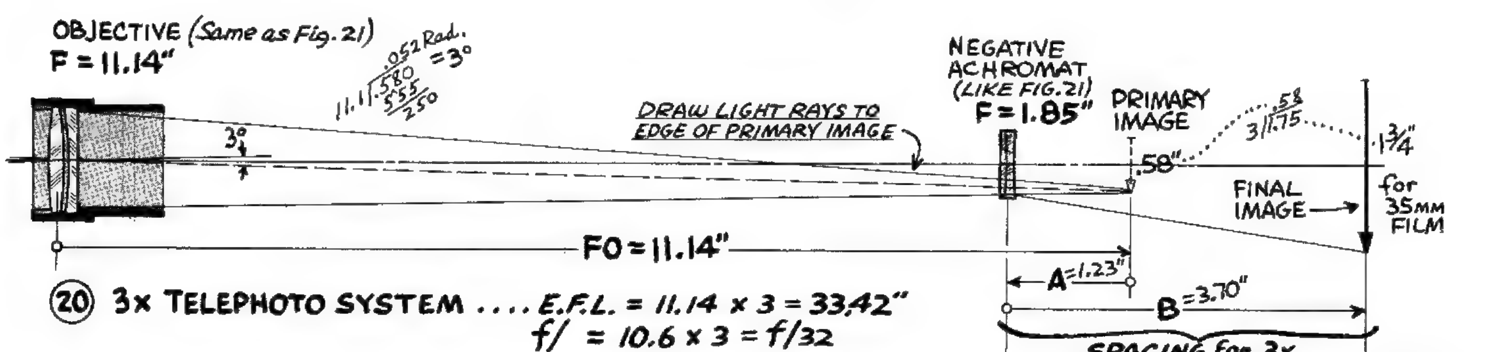
		Example
CASE 5-1	$B = (M-1)F$	$(2-1)\times 8 = 8"$
CASE 5-4	$A = \frac{B}{M}$	$\frac{8}{2} = 4"$
ALL CASES	$M = \frac{B}{A}$	$\frac{8}{4} = 2\times$
	$E.F.L. = F_{POS} \times M$	$8 \times 2 = 16"$

optional: EXIT PUPIL. THIS IS A CASE 3 PROBLEM... IS IMAGE OF THE OBJECTIVE FORMED BY NEG. LENS

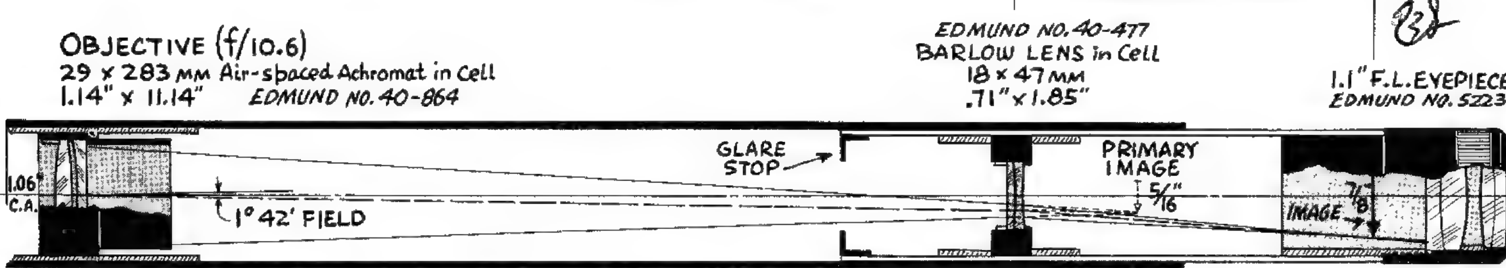
3-2	$B = \frac{F \times A}{F + A}$	$\frac{8\times 4}{8+4} = \frac{32}{12} = 2.66"$
	$M = \frac{B}{A}$	$\frac{2.66}{4} = .66\times$
	DIA. of E.P. = C.A. OBJ. × M	$1.5 \times .66 = 1"$

method shown. Like the Galilean telescope, the exit pupil is a virtual image between the lenses. On the optical bench, you can increase the telephoto effect, that is, increase the magnification, by pushing the negative lens forward. You then have to pull the tracing paper screen back to recapture the image. While commercial telephoto lenses are usually close-spaced for compactness, the homemade design usually runs to a stronger (shorter f.l.) negative lens at a greater distance from the primary objective. Fig. 20 illustrates.

BARLOW LENS. The Barlow lens is a particular form of the telephoto system. Its distinguishing feature is that it uses a comparatively short f.l. negative lens quite close to the primary image. Fig. 20 telephoto lens is actually a Barlow



(20) 3x TELEPHOTO SYSTEM .... E.F.L. = 11.14 × 3 = 33.42"
f/ = 10.6 × 3 = f/32



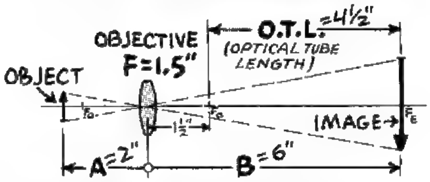
(21) ... SAME ... 30x ASTRO TELESCOPE

EYEPIECE WITH BARLOW LENS IS A 3X SETUP and CAN BE USED WITH ANY OBJECTIVE OR TELESCOPE IF THE PRIMARY IMAGE IS AT THE POSITION SHOWN

whole TELESCOPE about 15½" LONG

11/22

MICROSCOPE ㉒ Arithmetic



PRIMARY MAGNIFICATION

CASE 1-9 $M = \frac{B-F}{F}$ $\quad \frac{6-1.5}{1.5} = \frac{4.5}{1.5} = 3\times$

CASE 1-1 $B = (M+1)F$ $\quad (3+1)\times 1.5 = 6''$

CASE 1-4 $A = \frac{B}{M}$ $\quad \frac{6}{3} = 2''$

SPECIAL $M = \frac{O.T.L.}{F}$ $\quad \frac{4.5}{1.5} = 3\times$

COMPARE WITH CASE 1-9 above

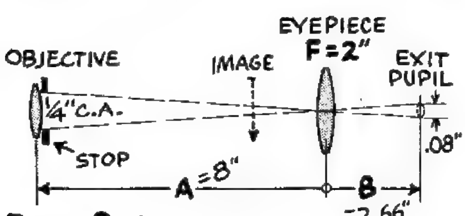
EYEPIECE M. IS RATED LIKE A SIMPLE MAGNIFIER:

$EYPC.\ M = \frac{10}{FE}$ (Inches) OR $\frac{250}{FE}$ (MM)

Example: $EYPC.\ M = \frac{10}{2} = 5\times$

WHOLE M. IS THE PRIMARY M MULTIPLIED BY THE EYEPIECE M

Example: 3x times 5x = 15x



EXIT PUPIL

CASE 1-2 $B = \frac{F \times A}{A-F}$ $\quad \frac{2\times 8}{8-2} = \frac{16}{6} = 2.66''$

ALL CASES $M = \frac{B}{A}$ $\quad \frac{2.66}{8} = .33\times$

DIA. of EXIT PUPIL = $.25 \times .33 = .082''$ (C.A. Obj.)

ANGULAR FIELD (Radians) $= \frac{C.A.\ EYPC.}{d} = \frac{.6}{8} = .075$ Rad.

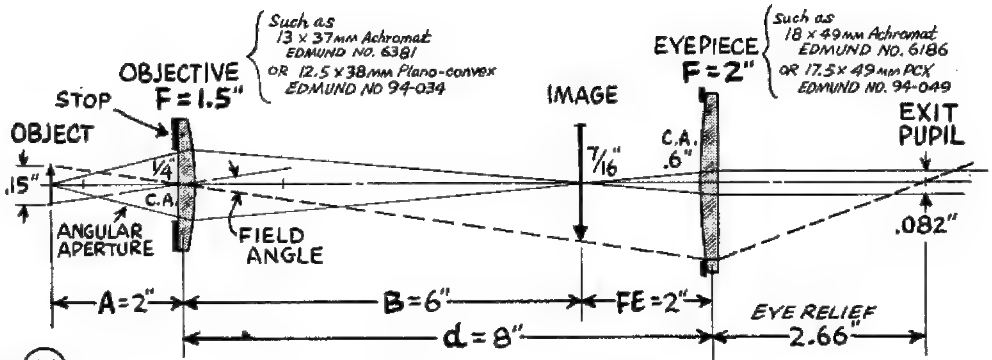
LINEAR FIELD = ANG. FIELD (Radians) × WORKING DISTANCE

$= .075 \times 2 = .15''\ (\frac{5}{32}'')$

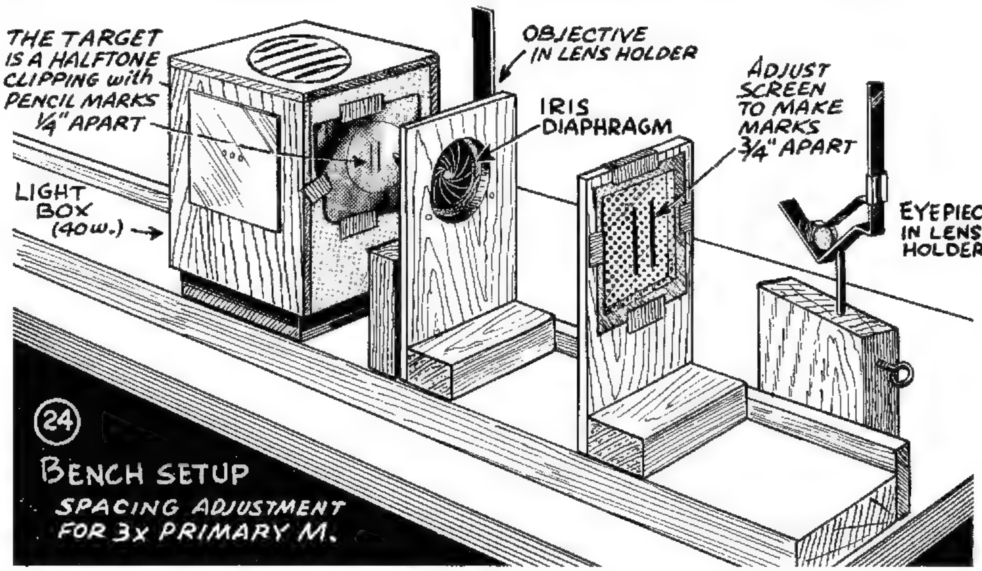
NUMERICAL APERTURE, IF 0.30 OR LESS, CAN BE TAKEN AS ½ THE ANGULAR APERTURE IN RADIANS

ANGULAR APERTURE (Radians) $= \frac{.25}{2} = .12$ Radians (C.A. Obj. / WORKING DISTANCE)

$N.A. = .12/2 = .06$



㉓ 15x MICROSCOPE FIELD - 0.15" (4MM) N.A. - 0.06

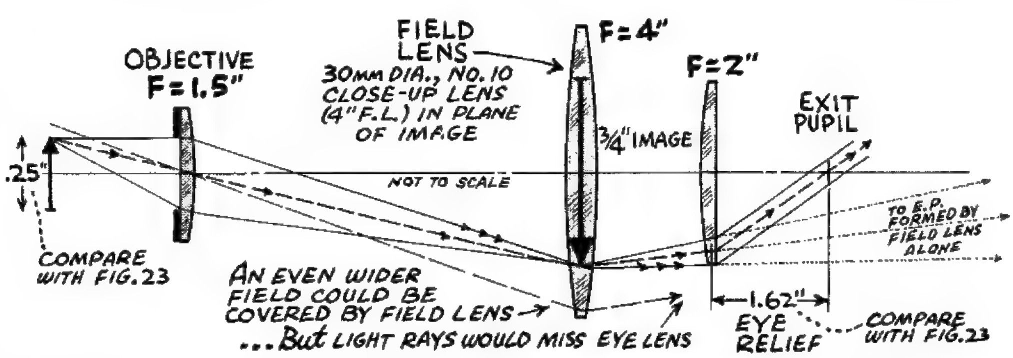


㉔ BENCH SETUP
SPACING ADJUSTMENT FOR 3x PRIMARY M.

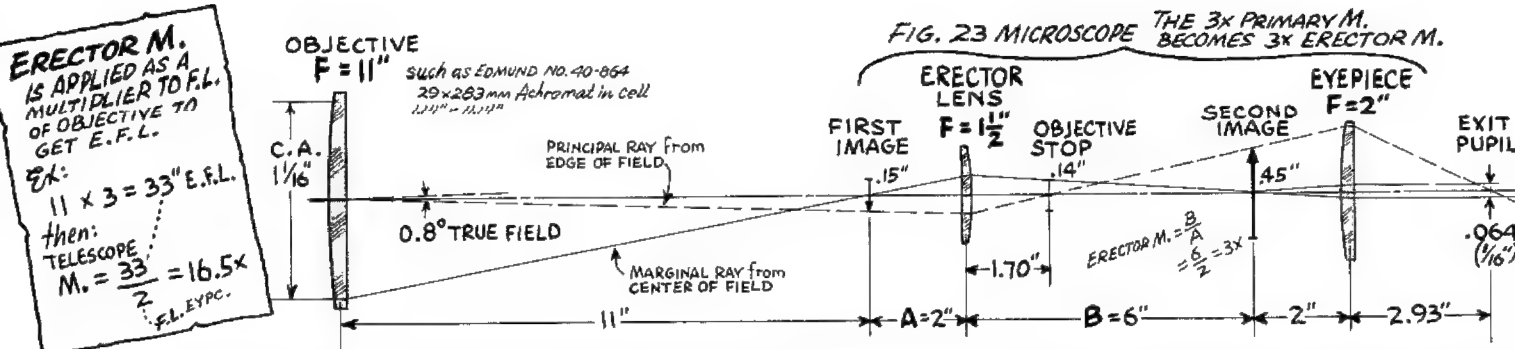
system in a permanent assembly. Fig. 21 shows another use of the negative lens in a fixed position.

THE MICROSCOPE. The microscope works at short range and so is different from a telescope which it resembles. The front lens or objective forms a magnified image by simple projection. The eyepiece then views the primary image and magnifies it still more. The total magnification is the primary M. multiplied by the eyepiece M.

Fig. 23 shows a typical demonstration microscope. It is set up for 3x primary M., but if you want more, all you need do is increase distance B. The target is a piece of halftone screen from any magazine or newspaper. In addition, you make two pencil marks 1/4 in. apart on the target, as can be seen in Fig. 24. The idea, of course,

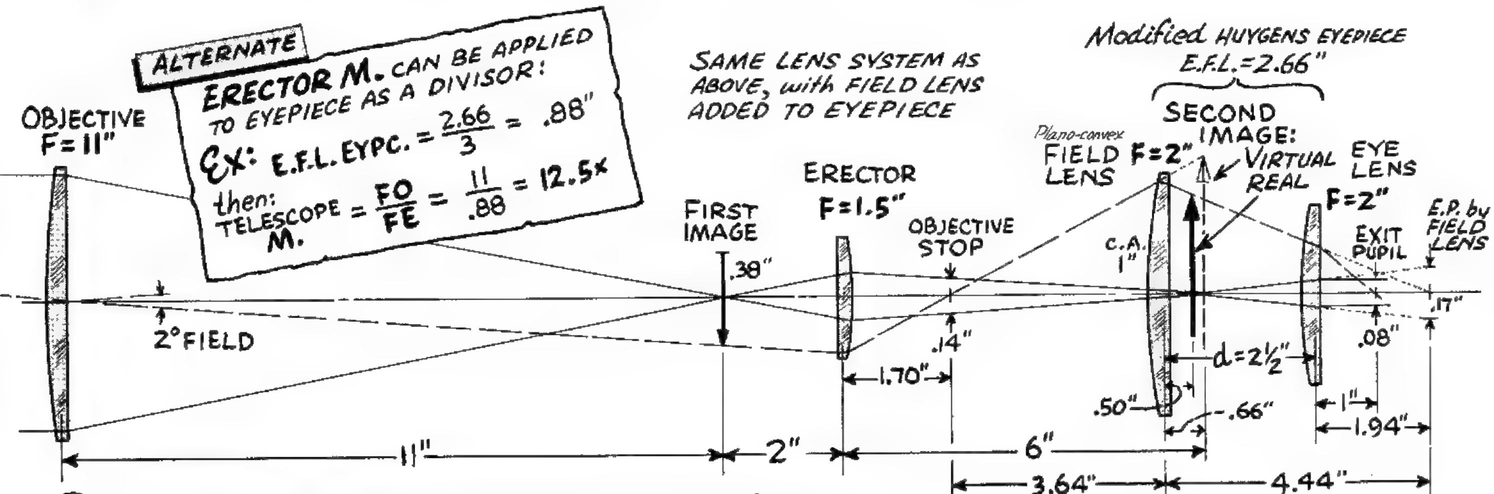


㉕ FIELD LENS INCREASES FIELD and SHORTENS EYE RELIEF



(26) *Microscope is Easily changed to TELESCOPE*

16.5x TERRESTRIAL TELESCOPE



(27) **12.5x TERRESTRIAL TELESCOPE with 2° FIELD**

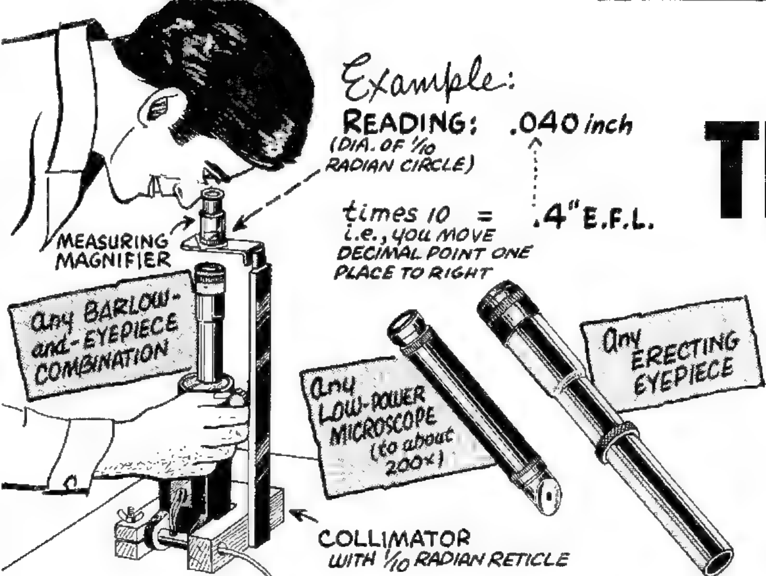
is that if you want 3x primary M., you juggle the spacing as needed until the image on the tracing paper screen is dead sharp and exactly 3/4 in. between the two lines. The eye lens is then put in place to complete the setup. You will note fast enough that the eye relief is too long, and the field of view rather small. The remedy is the same as for a telescope--you use a field lens, Fig. 25. The 4 in. f.l. shown is a bit too long, but you can see it makes an improvement.

The math work for a microscope is covered in Fig. 22. The common standard for the "optical tube length" is 160 mm. but there are departures from this. Commercial objectives are usually power-rated on the basis of a 160 mm. focal length is power-rated 160/16, is 10x. On the other hand, it may be an objective for a "student" microscope with, say, 127 mm. optical tube, in which case it would be power-rated 127/16, is 8x. The only sure thing about this muddle is that every manufacturer understands mm. optical tube. Example: An objective of 16 his own system. Microscope objectives are often used for other purposes, and in such case it is a good idea to check the actual focal length.

The exit pupil forms behind the eyepiece just like a telescope, but its diameter is not related to the power of the optical system.

TERRESTRIAL TELESCOPE. If you add a second objective to a microscope you get a terrestrial telescope, Fig. 26. The original microscope objective now becomes an erecting and amplifying lens for the telescope. Like the demo microscope, you will find the eye relief long and the field small, and as before, the solution is a field lens. This time you make it shorter f.l. to get a short but comfortable eye relief of 1 inch. As shown in Fig. 27, the field lens is located a little ahead of the image plane. This costs a little in reduced power, but compensations are the wider field and clearer image, the field lens surface being out of focus. You can also use a Ramsden eyepiece if desired, in which case the image will be in front of the field lens.

If you are drawing a diagram like Fig. 27, you find the exit pupil for the field lens alone, and this tells the path of the light rays. You can do-and-see this on the bench, using a tracing paper screen to pick up the EP, or, you can work it out with simple math. Note in the diagrams how the erector lens itself forms an image of the objective. This image is called the objective stop. The objective stop then becomes the object for following lenses; the distance from eyepiece to objective stop is what you consider in designing a suitable Huygens eyepiece.



TESTING Methods

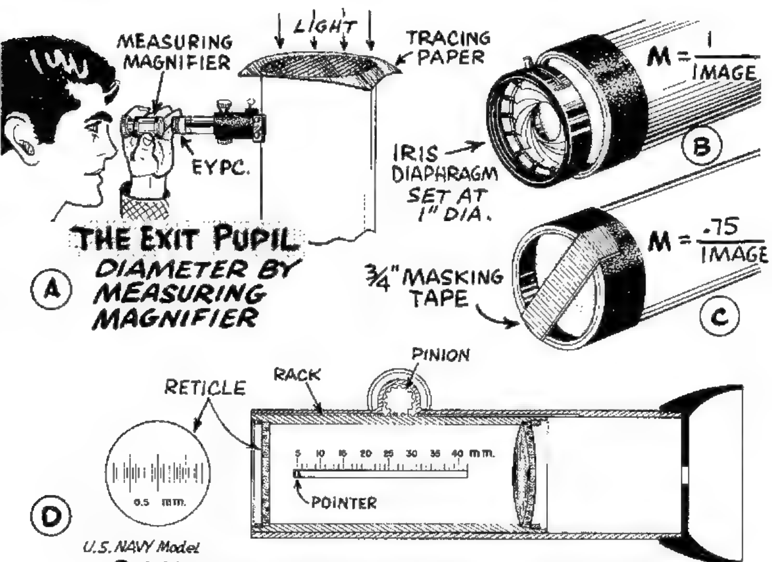
COLLIMATOR GIVES DIRECT READING OF E.F.L.

for Microscopes				Formula: $M = \frac{1}{\text{COLLI. READING}}$			
COLLI. READING	M.	COLLI. READING	M.	COLLI. READING	M.	COLLI. READING	M.
.050"	20×	.030"	33×	.016"	63×	.008"	125×
.045	22×	.025	40×	.014	71×	.006	167×
.040	25×	.020	50×	.012	83×	.005	200×
.035	29×	.018	56×	.010	100×	.003	333×

COLLIMATOR TELLS FOCAL LENGTH. A collimator with 1/10 radian target will tell the focal length of any lens or eyepiece. The same procedure applies to complete microscopes and other lens assemblies. The telescope is an exception. As already described on other pages, you simply get a sharp image of the collimator target on a tracing paper screen and then measure the diameter of the image in thousandths-of-an-inch with a measuring magnifier. This figure--times 10--is the f.l. of the lens or instrument. Ideal equipment for this test is the vertical collimator described on other pages; use it with a piece of tracing paper under the measuring magnifier for best illumination.

The example at left is an Edmund achromatic Barlow of 1.83 inch f.l. combined with Edmund No. 5223 eyepiece of 28mm focal length. With the Barlow lens at lower end of the Barlow tube, the image reads .040 inch, indicating an e.f.l. of 4/10 inch for the combination.

For low-power microscopes, the table converts e.f.l. to magnifying power. It will be noted that hi-power microscopes require critical reading of the image size; the reading can be made more accurately with a measuring microscope used in the same manner as a measuring magnifier.



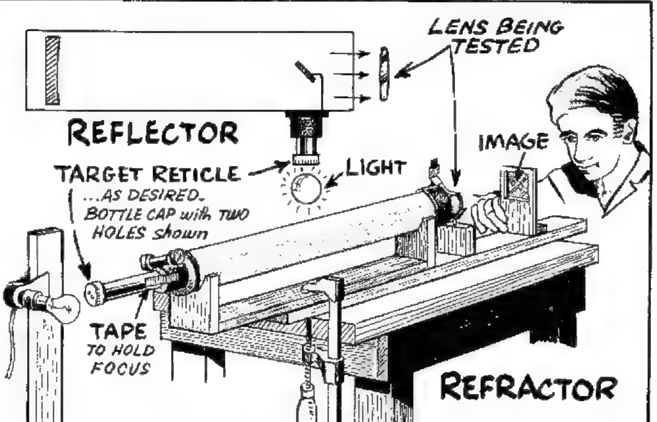
DYNAMETER READS E.P. DIA. and EYE RELIEF

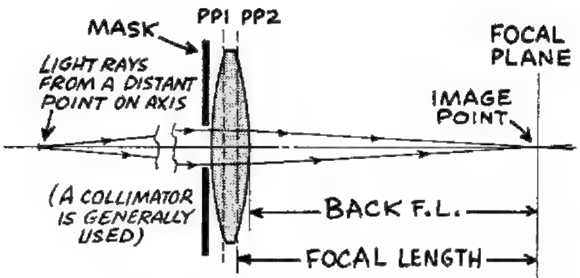
THE EXIT PUPIL. Use a measuring magnifier to find the exact diameter of the exit pupil. This simple operation applied to a reflecting telescope is shown at left. If, while doing this, you anchor your little finger on the eyepiece, as shown, you can then measure the eye relief with a ruler. An instrument known as a dynameter, Fig. D, does the job in one operation.

You can find the magnifying power of a telescope by dividing the diameter of the objective by the diameter of the exit pupil. It is common and sensible practice to use something less than full objective diameter. For example, an iris diaphragm set at 1-inch may be used, as shown, or, you can use a strip of masking tape as at C. In each case, the small separation from the objective surface itself will not change the exit pupil reading. A pair of dividers set at 1 inch provides another popular target for making this test.

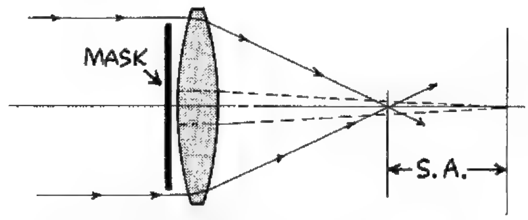
any telescope a COLLIMATOR

Find the exact focal plane beforehand by focusing the moon on a tracing paper screen at the end of the focusing tube. The same screen with a few random ink marks will provide a simple reticle. A large pinhole in metal (shown) gives stronger illumination. Of course the scope is ideal for a small pinhole (artificial star). For a focal collimator, the best you can do is 1/40 radian, which is a 1-1/8-inch circle for a 45 in. f.l. objective (1/40 times 45). Since the target is 1/40 radian, the constant multiplier to be applied to the image size is 40.



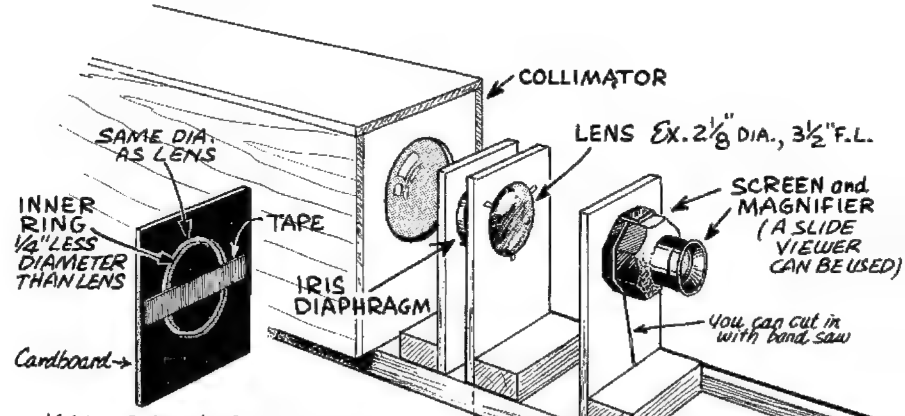


PARALLEL LIGHT RAYS PASSING THRU CENTER ZONE OF A LENS OR MIRROR ESTABLISH THE FOCAL PLANE and F.L.



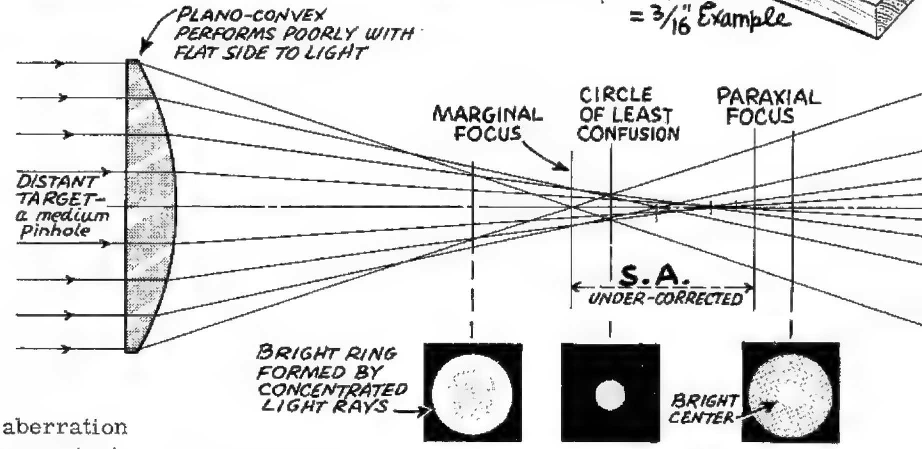
IF MARGINAL RAYS FOCUS CLOSER TO LENS, THE LENS (OR MIRROR) IS SPHERICALLY UNDER-CORRECTED.

FOR A DISTANT TARGET, ALL SIMPLE POSITIVE LENSES and MIRRORS HAVE UNDER-CORRECTED S.A.



MASK FOR MARGINAL ZONE

SPHERICAL ABERRATION

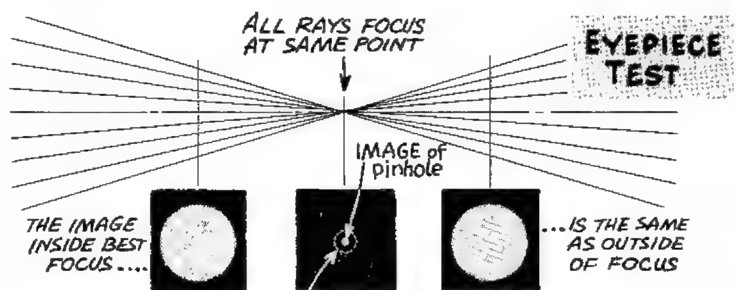


THE IMAGE SHOWS CONCENTRATIONS OF LIGHT RAYS

SPHERICAL ABERRATION. When spherical aberration is pronounced, it is readily determined and demonstrated with a simple zone test. The test is usually made with a collimator with any black-on-white target. The drawing above shows the setup. To isolate the center zone of the lens, you can use an iris diaphragm. The edge zone mask is made from cardboard, exposing a narrow rim of the lens about 1/8 in. wide. Both zones are carefully focused, using a magnifier to view the image on tracing paper or ground glass screen. The difference in the two image planes is the amount of S.A. It is positive or under-corrected if the edge rays focus short, as shown in the example. Further refinements can be made in the number of masks used and the size of the zone exposed for testing.

Eyepiece Test. Spherical aberration in a telescope can be detected by looking at a pinhole target. No masks are used. The target pinhole can be either open-air or by collimator, its diameter several times larger than for the similar "star" test described later. As shown in the lower diagram at right, a lens free of S.A. will produce a small bright image at best focus. Inside or outside best focus, the image will be expanded and grayer, but its appearance will be substantially the same in either position. If there is spherical aberration, the center of image is brighter on one side of best focus while the edge is brighter on the other side. This test tells only if S.A. is present, but not how much.

EYEPIECE TEST



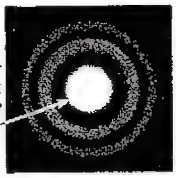
PERFECT LENS with no S.A.

STAR TEST. This is the same general idea as the eyepiece test just described, except the pinhole is made small enough to simulate the performance of a real star. This makes the test much more sensitive. What you see is a diffraction pattern consisting of a bright disk surrounded by one or more rings. A collimator provides a convenient setup, but it needs a very tiny and expensive (if purchased) pinhole, plus brilliant lighting. Most amateurs use an open-air target.

Tiny pinholes are pricked with a fine needle in aluminum foil backed with a sheet of plastic or glass. You can do better work with the needle mounted in a dowel stick. Press very lightly and give the dowel handle a full turn. First attempts will show holes about .005 inch diameter when viewed with a measuring magnifier. It takes a lot of practice and maybe a little luck to make holes smaller than .001 inch.

Because the pinhole is small, intense light is required. A simple and practical setup for pinholes .001 inch or larger can be made with a slide projector, as shown. To put the target somewhere near practical infinity, you need at least 60 ft. However, testing at 20 ft. is possible, although it makes the whole test of doubtful value. If you fail to see rings, it is likely your pinhole is too large. An easy remedy is to stop down, which of course further nullifies the test itself--but

STAR TESTING



DIFFRACTION DISK OF A STAR AS SEEN WITH GOOD OPTICS AT HIGH M.

Micron CONVERSIONS

MICRONS =	MM. =	INCHES
*1µ	.001mm	.00004"
2	.002	.00008
3	.003	.00012
4	.004	.00016
*5	.005	.00020
*10	.010	.0004
15	.015	.0006
20	.020	.0008
*25	.025	.001

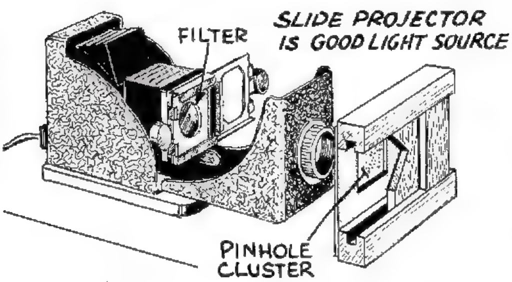
*STANDARD COMMERCIAL PINHOLES

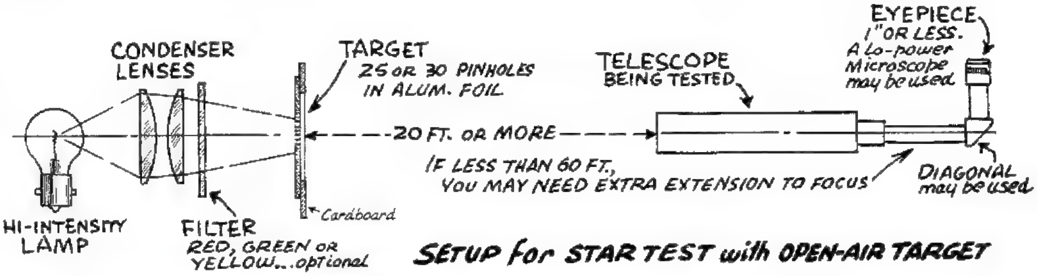
DIAMETER OF PINHOLE FOR STAR TESTING

COLLIMATOR OR TELESCOPE LENS OR MIRROR

ANGULAR SIZE * (Radians)	APERTURE	*DISTANCE FROM PINHOLE TO LENS (OR MIRROR) 24" 2 Ft.	48" 4 Ft.	96" 8 Ft.	120" 10 Ft.	240" 20 Ft.	480" 40 Ft.	720" 60 Ft.	960" 80 Ft.	1200" 100 Ft.	2400" 200 Ft.
.000044	1/2"	.001"	.002"	.004"	.005"	.010"	.021"	.031"	.042"	.052"	.105"
.000022	1"	.0005	.0010	.002	.0026	.005	.010	.015	.021	.026	.052
.000015	1½"	.0003	.0007	.0014	.0017	.0035	.007	.010	.014	.017	.035
.000011	2"	.00026	.0005	.0010	.0013	.0026	.005	.007	.010	.013	.026
.0000074	3"	.00017	.00035	.0007	.0009	.0017	.003	.005	.007	.008	.017
.0000055	4"	.00013	.00026	.0005	.0006	.0013	.0026	.004	.005	.006	.013
.0000044	5"	.00010	.00020	.0004	.0005	.0010	.0020	.003	.004	.005	.010
.0000037	6"	.00008	.00016	.00034	.0004	.0008	.0017	.0025	.003	.004	.008
.0000028	8"	.00007	.00013	.00026	.0003	.0006	.0013	.0020	.0026	.0033	.006
.0000022	10"	.00005	.00010	.00021	.0002	.0005	.0010	.0015	.0021	.0026	.005

*FOR DISTANCES NOT LISTED: Multiply RADIAN VALUE BY DISTANCE IN INCHES





SETUP For STAR TEST with OPEN-AIR TARGET

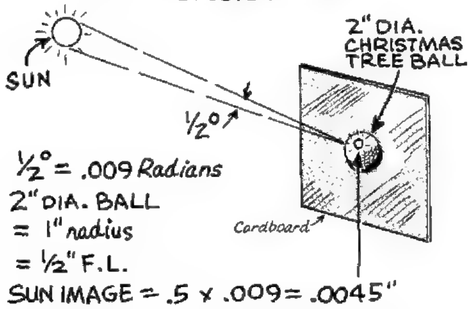
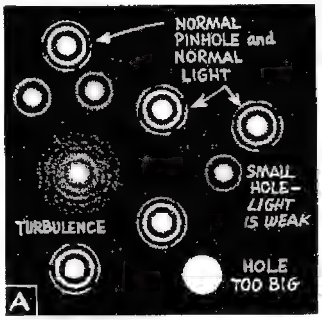
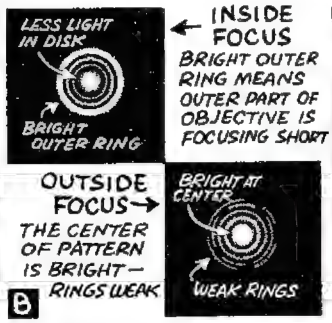


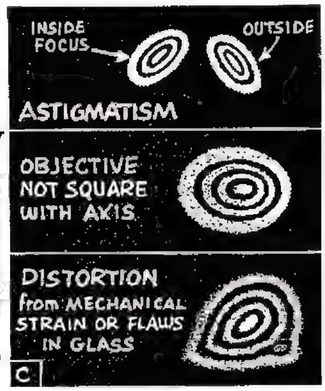
IMAGE of SUN Can be your TARGET



PINHOLE CLUSTER VIEWED AT BEST FOCUS. GOOD OBJECTIVE. TURBULENCE BY ELECTRIC FAN



SPHERICAL ABERRATION
Example IS UNDER-CORRECTED S.A.-THE EDGE RAYS are SHORT



you do get to see diffraction rings!

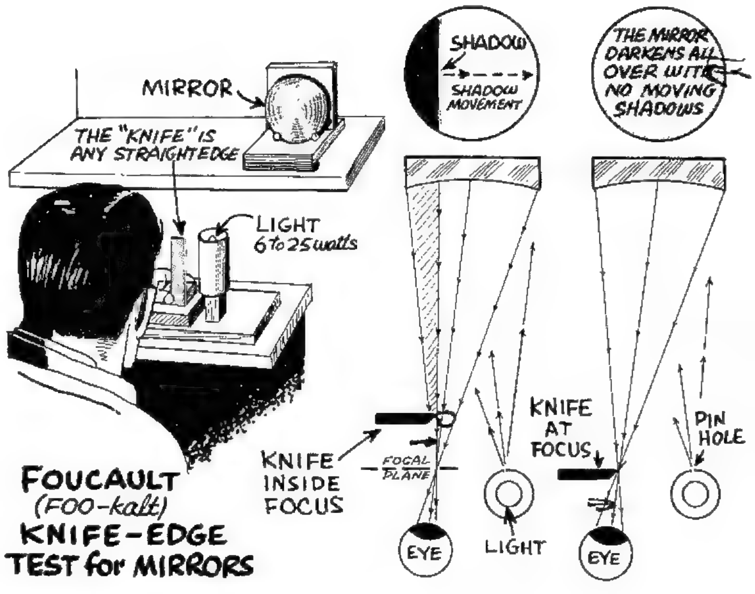
Normally you have to use a strong eyepiece--1/2 in. or less--to get enough M. to see the tiny image of the pinhole. An alternate is a 4 to 6x auxiliary telescope mounted behind a 1 inch eyepiece. If, say, 5x this increases the magnification 5 times, giving the equivalent of a 1/5 inch eyepiece--and you get comfortable eye relief. If you stop down to f/32 or greater f/number, the pinhole image will be larger, easy to see with a 1 inch eyepiece used alone. A low-power microscope is sometimes used to view the image, especially in connection with a collimator.

For a starter, it is best to view a cluster of pinholes since this will show variations caused by light intensity as related to hole size, Diagram A. Like the simpler eyepiece test, a bright ring inside focus means under-corrected S.A., Diagram B. If the image does a right-angle flip as viewed on either side of best focus, you have a plain case of astigmatism, as at C. If the pattern is not exactly round, it indicates a tilted objective--specifically, the edge of the objective lens opposite the brightest and least expanded part of the image is too close to the image. The opposite applies to a mirror objective.

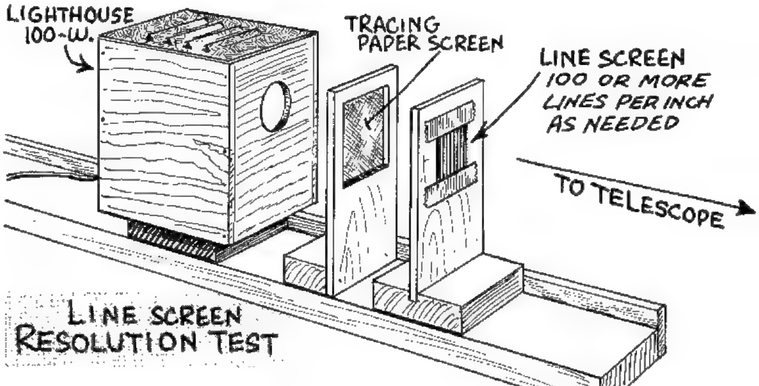
Extra-focal Images. The focusing movement inside or outside best focus is usually very short--1/8 inch or less. With further movement of 1/2 inch or more, you can watch the whole process of a diffraction disk being born, growing out of a tiny black speck at the center of the primary image. This is seen best with a refractor since the diagonal mirror of a reflector blocks out the center of the diffraction pattern. The extra-focal images are hairy with wide flaring rings. However, the pattern remains concentric for a properly centered system; also, similar appearance inside and outside means freedom from spherical aberration.

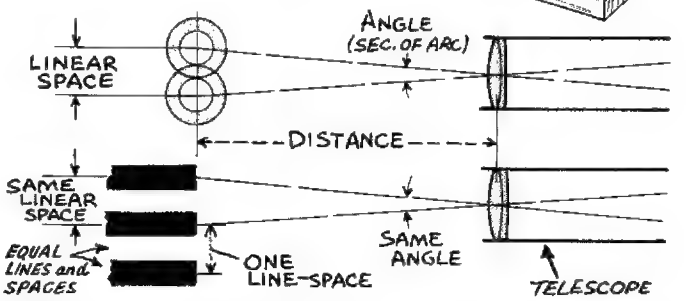
FOUCAULT KNIFE-EDGE TEST. Frenchman Jean Bernard Leon Foucault developed this technique in 1859, since when it has been the No. 1 test method for testing mirrors. In this test, light from a pinhole or slit at the center of curvature of the mirror is received directly into the eye, i.e., no eyepiece is used. What you look at is the face of the mirror itself, which can be either silvered or bare glass. The knife-edge is cut into the light beam, and with part of the light cut off in this manner, the face of the mirror is seen in a variety of shadow patterns, all fairly easy to interpret. The test provides an exact numerical value for spherical aberration. The light source is a weak 6 to 25-watts as compared to the powerful mini searchlights needed for the star test with artificial star.

The Foucault test is described in detail in several pages of the Edmund book, "All About Telescopes," which should be consulted if you are not familiar with the process.



RESOLUTION TEST. The simplest and perhaps best resolution test is done with either a collimator or open-air target of ruled lines. What you aim for, of course, is Dawes' Limit, and the line screen and viewing distance must be such as to produce the specified angle. This data is given in the table below. The target itself can be on film, glass or thin paper, illuminated from the rear, as shown in the drawing. Keep in mind that Dawes' limit is not something you are going to see real easy, nice and clear--if you can tell at all you are looking at a ruled screen, you're in! You can use any eyepiece magnification needed, since the whole idea is simply that the image is there at the image plane. For terrestrial telescopes and binoculars, a resolution of 8/A seconds of arc is a common standard; a 7 x 50 binocular, for example, should show the lines of a 4-second screen, but you will need a 4x auxiliary telescope to make the separation. It can be seen the apparent field angle will be a mere 28 seconds of arc (4 times 7), which your eyes will not be able to resolve. The 4x compounding of the magnification will make the apparent field nearly 2 minutes, which you should be able to see if the objective has done its job. A stronger auxiliary scope may be used if desired.



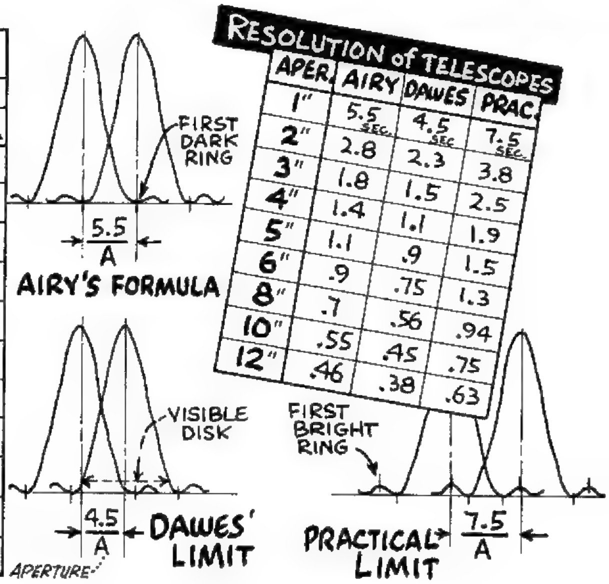


EQUIVALENT LUMINOUS POINTS and LINE-SCREEN TARGETS

ANGULAR SEPARATION of LINE SCREENS (SECONDS of ARC)

LINES PER INCH	ONE* LINE-SPACE	DISTANCE — LENS TO TARGET									
		2 FT.	4 FT.	8 FT.	10 FT.	20 FT.	40 FT.	60 FT.	80 FT.	100 FT.	200 FT.
1000	.001"	8 SEC.	4 SEC.	2.1	1.7	.8	.4	.29	.21	.16	.08
500	.002	17	8	4.2	3.4	1.7	.8	.58	.42	.32	.16
300	.0033	29	14	7.1	5.7	2.8	1.4	.96	.71	.55	.27
250	.004	34	17	8.4	6.8	3.4	1.7	1.2	.84	.64	.32
200	.005	43	21	11	8.5	4.3	2.1	1.4	1.1	.82	.41
150	.0066	57	29	14	11	5.7	2.8	1.9	1.4	1.1	.54
133	.0075	64	32	16	13	6.4	3.2	2.1	1.6	1.3	.64
100	.010	86	43	21	17	8.5	4.3	2.9	2.1	1.6	.82
80	.0125	107	54	27	21	11	5.3	3.6	2.7	2.1	1.0
65	.0154	132	66	33	26	13	6.6	4.4	3.3	2.6	1.3
50	.020	171	86	43	34	17	8.5	5.8	4.3	3.3	1.6

* from CENTER OF ONE LINE to CENTER OF NEXT LINE

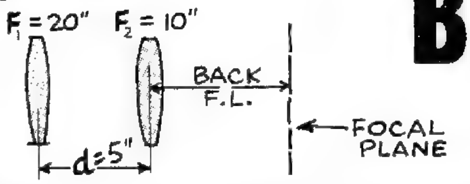


RESOLUTION of TELESCOPES

APER.	AIRY	DAWES	PRAC.
1"	5.5 SEC.	4.5 SEC.	7.5 SEC.
2"	2.8	2.3	3.8
3"	1.8	1.5	2.5
4"	1.4	1.1	1.9
5"	1.1	.9	1.5
6"	.9	.75	1.3
8"	.7	.56	.94
10"	.55	.45	.75
12"	.46	.38	.63

Problem:

①



Find EQUIVALENT F.L. and BACK F.L. of this DUPLET

FORMULA $E.F.L. = \frac{F_1 \times F_2}{F_1 + F_2 - d}$

SEE TABLE 1

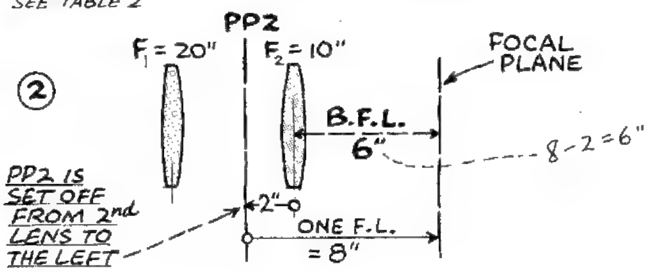
$$E.F.L. = \frac{20 \times 10}{20 + 10 - 5} = \frac{200}{25} = 8"$$

The B.F.L. CAN BE CALCULATED DIRECTLY (*SEE BELOW*), BUT IS USUALLY OBTAINED FROM THE CALCULATED POSITION OF PP2

FORMULA $PP2 = \frac{F_c \times d}{F_1} = \frac{8 \times 5}{20} = \frac{40}{20} = 2"$

SEE TABLE 2

②



TWO POSITIVE LENSES

DIRECT Calculation of BACK FOCAL LENGTH

③ *Example as above*

FORMULA $B.F.L. = \frac{F_2\,(F_1 - d)}{F_2 + F_1 - d} = \frac{10 \times (20 - 5)}{10 + 20 - 5}$

$$B.F.L. = \frac{10 \times (15)}{25} = \frac{150}{25} = 6"$$

F_c IS ANOTHER SYMBOL FOR E.F.L.

ALTERNATE

FORMULA $B.F.L. = \frac{F_c \times (F_1 - d)}{F_1} = \frac{8 \times (20 - 5)}{20}$

$$B.F.L. = \frac{8 \times 15}{20} = \frac{120}{20} = 6"$$

NOTE: IF d EXCEEDS F_1 YOU WILL GET A NEGATIVE NUMBER FOR THE B.F.L., INDICATING THE DISTANCE IS TO THE LEFT OF SECOND LENS

Basic Optical MATH

PERHAPS the two most common problems in optical math are (1) the equivalent focal length of two lenses, and (2) the position of the image produced by a lens or mirror. You can solve these and many other problems with the help of the simple equations given in Tables 1, 2 and 3.

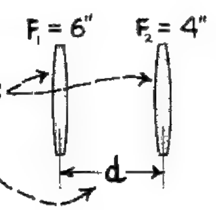
EQUIVALENT FOCAL LENGTH. Two or more lenses can be put together in various ways to form a lens system. The most common case is where both lenses are positive. If you study the examples in Table 1 you will note that the least equivalent focal length is obtained when the air space is zero. As might be expected, the e.f.l. increases when the air space is increased, reaching a limit when the spacing equals the combined focal lengths of the two lenses. This particular spacing forms the familiar astronomical telescope, with an equivalent focal length which in infinite. Normally, the spacing of a positive duplet is less than the longer of the two lenses used. Greater spacing will produce a virtual image receding to the left.

The lenses used in Fig. 1 calculation are Plus 2 and Plus 4 diopters, items you will find in any set of supplementary close-up lenses used for photography. Spaced at 5 inches, this combination has a focal length of 8 inches, as shown. If you have the lenses on hand, it is interesting and instructive to see what happens when you vary the air space.

PRINCIPAL PLANES. After you have calculated the e.f.l. of a duplet, you are still shy needed data to determine the focal plane. Of course, this is something you can find instantly if you have the lenses set up on the optical bench. As a math

E.F.L. Controlled by SPACING

The SETUP:
ANY TWO LENSES
ANY SPACING



E.F.L. RANGE:

THE LEAST F.L. IS OBTAINED WHEN d = ZERO

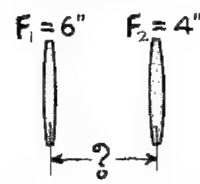
for the Example:

$$LEAST\ F.L. = \frac{6 \times 4}{6 + 4} = \frac{24}{10} = 2.4"$$

BY INCREASING THE SPACE, YOU CAN GET *ANY* FOCAL LENGTH OVER 2.4"

Example:

You want E.F.L. = 3"



FORMULA: $d = F_1 + F_2 - \frac{F_1 \times F_2}{E.F.L.}$

(FOR TWO POSITIVE LENSES)

$$= 6 + 4 - \frac{\cancel{6}^{2} \times 4}{\cancel{3}}$$

$$d = 10 - 8 = 2"$$

Check

$$E.F.L. = \frac{6 \times 4}{6 + 4 - 2} = \frac{24}{8} = 3"$$ OK

TABLE 1

Equivalent Focal Length of Two Lenses

	TWO POSITIVE	TWO NEGATIVE	POSITIVE and NEGATIVE: NEGATIVE is LONGER	POSITIVE and NEGATIVE: NEG. is SHORTER F.L.
BASIC FORMULA	E.F.L. = $\frac{F \times F}{F + F - d}$ (F.L. of FIRST LENS; F.L. of SECOND LENS; SPACING)	E.F.L. (NEGATIVE) = $\frac{F \times F}{F + F + d}$	E.F.L. = $\frac{POS \times NEG}{NEG - POS + d}$	E.F.L. (NEGATIVE) = $\frac{POS \times NEG}{POS - NEG - d}$
Examples: CONTACT	F=6" F=4" F.L. of COMBINED LENSES, d=0 (NEARLY) $F_c = \frac{6\times4}{6+4-0} = \frac{24}{10} = 2.4"$	F=6" F=4" d=0 (NEARLY) $F_c = \frac{6\times4}{6+4+0} = \frac{24}{10} = 2.4"$ NEG.	F=2" POS F=4" NEG d=0 (NEARLY) $F_c = \frac{2\times4}{4-2+0} = \frac{8}{2} = 4"$	F=4" POS F=2" NEG d=0 (NEARLY) $F_c = \frac{4\times2}{4-2-0} = \frac{8}{2} = 4"$ NEG.
MODERATE SPACING	6" 4" d = 2" $F_c = \frac{6\times4}{6+4-2} = \frac{24}{8} = 3"$	6" 4" d = 2" $F_c = \frac{6\times4}{6+4+2} = \frac{24}{12} = 2"$ NEG.	2" POS 4" NEG d = 1" $F_c = \frac{2\times4}{4-2+1} = \frac{8}{3} = 2.66"$	4" POS 2" NEG d = 1" $F_c = \frac{4\times2}{4-2-1} = \frac{8}{1} = 8"$ NEG.
SPACING LIMIT (IF ANY)	6" 4" 6+4 d = 10" LIMIT: $d = F_1 + F_2$ $F_c = \frac{6\times4}{6+4-10} = \frac{24}{0} = \infty$ THE F.L. OF COMBINED LENSES IS INFINITE. THIS IS SYSTEM OF ASTRO TELESCOPE	NO SPACING LIMIT. NO CHANGE IN FORMULA. *E.F.L. ALWAYS NEGATIVE and DECREASES WITH INCREASED SPACING*	NO SPACING LIMIT. NO CHANGE IN FORMULA. *THE E.F.L. (F_c) IS ALWAYS POSITIVE and BECOMES LESS WITH INCREASED SPACING*	4" 2" 4-2 d = 2" LIMIT: d = POS−NEG $F_c = \frac{4\times2}{4-2-2} = \frac{8}{0} = \infty$ THE F.L. IS INFINITE. THIS IS SYSTEM OF A GALILEAN TELESCOPE
SPACING OVER THE LIMIT	change FORMULA: E.F.L. (NEGATIVE) = $\frac{F \times F}{d - (F+F)}$ 6" 4" d = 12" $F_c = \frac{6\times4}{12-(6+4)} = \frac{24}{2} = 12"$ NEG. *COMPOUND SYSTEM IS BASIS FOR PROJECTION and THE MICROSCOPE*	*NO LIMIT* **Sample:** 6" 4" d = 10" $F_c = \frac{6\times4}{6+4+10} = \frac{24}{20} = 1.2"$ NEG.	*NO LIMIT* **Sample:** 2" POS 4" NEG d = 10" $F_c = \frac{2\times4}{4-2+10} = \frac{8}{12} = .66"$	change FORMULA: E.F.L. (POSITIVE) = $\frac{POS \times NEG}{NEG + d - POS}$ 4" POS 2" NEG d = 3" $F_c = \frac{4\times2}{2+3-4} = \frac{8}{1} = 8"$ *COMPOUND SYSTEM USED FOR TELEPHOTO LENSES and BARLOW SYSTEMS*

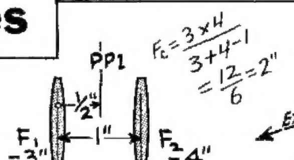
NOTE: ALL FORMULAS ARE ARRANGED TO BE WORKED BY SIMPLE ARITHMETIC ... MINUS MEANS ONLY SUBTRACTION

TABLE 2

Principal Planes

Standard FORMULAS:

DISTANCE from FIRST LENS (or PP1 of First Lens) TO PP1 of COMBINATION = $\frac{F_c \times d}{F_2}$ (Spacing)

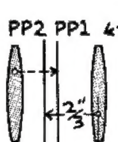


Example: $\frac{2 \times 1}{4} = \frac{2}{4} = \frac{1"}{2}$

DISTANCE from SECOND LENS (or PP2 of Second Lens) TO PP2 of COMBINATION = $\frac{F_c \times d}{F_1} = \frac{2\times1}{3} = \frac{2"}{3}$

THESE FORMULAS APPLY TO ALL CASES

IF THE TWO LENSES ARE IDENTICAL, THE PP's WILL BE SYMMETRICAL



THE PP's ARE "CROSSED." THIS IS ALWAYS THE CASE WITH POSITIVE LENSES UNLESS SPACING IS VERY CLOSE

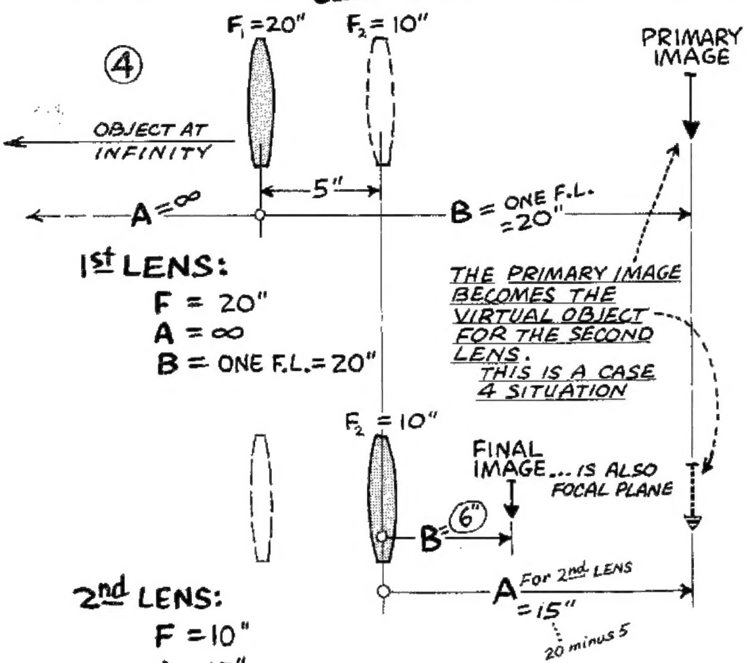
PP DIRECTION ... spacing (d) less than Limit

	TWO POS.	TWO NEG.	POSITIVE and NEGATIVE: NEG. Longer, POS. First	NEG. Longer, NEG. First	NEG. Shorter, POS. First	NEG. Shorter, NEG. First
PP1	RIGHT	RIGHT	LEFT	RIGHT	RIGHT	LEFT
PP2	LEFT	LEFT	LEFT	RIGHT	RIGHT	LEFT
Order	USUALLY CROSSED	NORMAL	NORMAL	NORMAL	CROSSED	CROSSED

... spacing MORE than limit

	TWO POS.	TWO NEG.	POSITIVE and NEGATIVE: NEG. Longer, POS. First	NEG. Longer, NEG. First	NEG. Shorter, POS. First	NEG. Shorter, NEG. First
PP1	LEFT	—	—	—	LEFT	RIGHT
PP2	RIGHT	AS ABOVE	AS ABOVE	AS ABOVE	LEFT	RIGHT
Order	NORMAL	—	—	—	NORMAL	NORMAL

TWO POSITIVE LENSES
OBJECT-IMAGE *Calculation* LENS-BY-LENS



1st LENS:

F = 20″
A = ∞
B = ONE F.L. = 20″

2nd LENS:

F = 10″
A = 15″

CASE 4-2 $B = \frac{F \times A}{F + A} = \frac{10 \times 15}{10 + 15} = \frac{150}{25} = 6''$

...add operations (OPTIONAL)

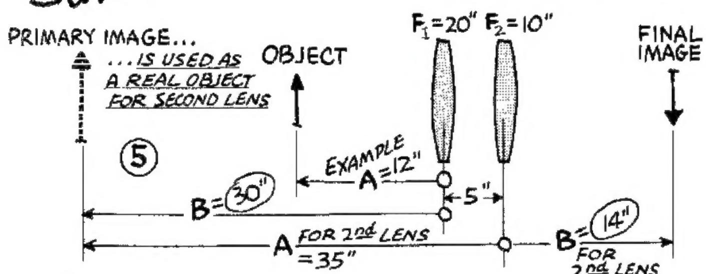
CASE 4-7 $M = \frac{B}{A} = \frac{6}{15} = .4\times$

FORMULA E.F.L. = F_1 × M of 2nd LENS = 20 × .4 = 8.0″

WITH ORIGINAL OBJECT AT ∞

(You CAN USE THIS FORMULA FOR ANY 2-LENS COMBO)

Same LENS SYSTEM as above but NEAR OBJECT



1st LENS:

F = 20″
A = 12″ *(THIS IS LESS THAN F_1 SO IS CASE 2)*

CASE 2-2 $B = \frac{F \times A}{F - A} = \frac{20 \times 12}{20 - 12} = \frac{240}{8} = 30''$ *(TO LEFT)*

$M = \frac{B}{A} = \frac{30}{12} = 2.5\times$

2nd LENS:

F = 10″
A = 35″ (30″ + 5″)

CASE 1-2 $B = \frac{F \times A}{A - F} = \frac{10 \times 35}{35 - 10} = \frac{350}{25} = 14''$

$M = B/A = 14/35 = .4\times$

whole M = M of 1st LENS times M of 2nd = 2.5 × .4 = 1×

THE IMAGE IS SAME SIZE AS OBJECT

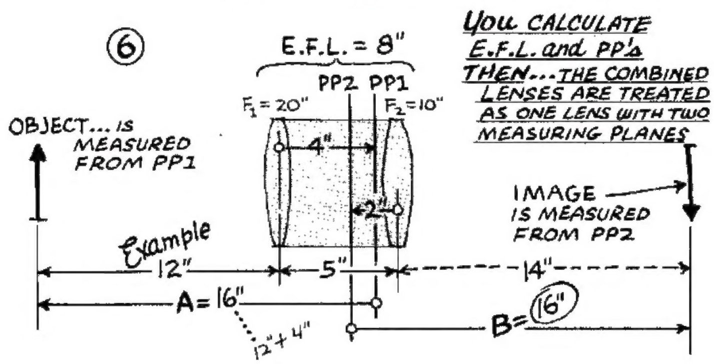
problem, you have to locate the position of Principal Plane No. 2, this being the reference line from which the rear focal plane is measured. Table 2 gives the needed formulas which are the same for all lens combinations except as regards the direction in which the measurement is made. Fig. 2 works out a sample calculation, this being a continuation of the same setup shown in Fig. 1. You now have all the basic data for this particular lens system. If desired you can locate the rear focal plane by a direct calculation of the back focal length, as shown in Fig. 3 example.

OBJECT-IMAGE MATH. The four quantities involved in any object-image calculation are shown at the top of Table 3. If you know or can specify any two of these, you can calculate the other two. The six standard cases shown will handle practically any situation.

Where two lenses are involved, as for Cases 4, 5, and 6, you have a choice of method in making the calculation. One method is to calculate the image position lens-by-lens. In this method, the image formed by the first lens becomes the object for the second lens. Fig. 4 is a typical example. Fig. 5 shows the calculation for the same lens system, but with a near object.

Fig. 6 shows the alternate method. In this method, you calculate the e.f.l. and PP's of the combined lenses, after which you can treat the combination as a single lens with two reference planes. It is then a Case 1 problem. Naturally, you get the same answer with either method. With a near object, as in this example, it is usually simpler to convert the combination to its single lens equivalent.

Same SETUP AS FIG. 5 but OBJECT-IMAGE CALCULATION made from PP's



F = 8″
A = 16″ (12″ + 4″)

CASE 1-2 $B = \frac{F \times A}{A - F} = \frac{8 \times 16}{16 - 8} = \frac{128}{8} = 16''$

CASE 1-7 $M = \frac{B}{A} = \frac{16}{16} = 1\times$ *(THE IMAGE IS SAME SIZE AS OBJECT)*

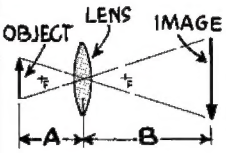
TABLE 3

A... is OBJECT DISTANCE from Lens
B... is IMAGE DISTANCE from Lens
F... is FOCAL LENGTH of Lens
M... is Linear MAGNIFICATION

OBJECT-IMAGE Equations

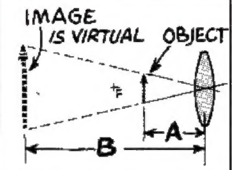
(THE EQUATIONS ARE ARRANGED FOR SOLUTION BY SIMPLE ARITHMETIC... MINUS MEANS ONLY SUBTRACTION)

CASE 1



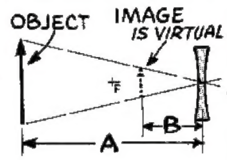
POSITIVE LENS WITH OBJECT AT MORE THAN ONE FOCAL LENGTH FROM THE LENS

CASE 2



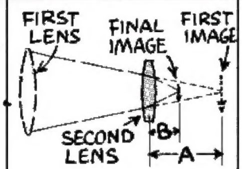
POSITIVE LENS WITH OBJECT AT LESS THAN ONE F.L. FROM LENS

CASE 3



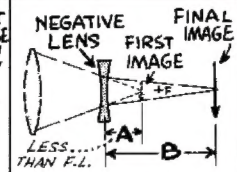
NEGATIVE LENS WITH OBJECT AT ANY DISTANCE

CASE 4



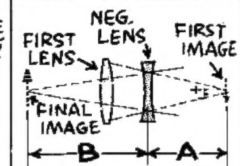
THE SECOND OF TWO POSITIVE LENSES WITH VIRTUAL OBJECT AT ANY DISTANCE TO THE RIGHT

CASE 5



THE NEGATIVE LENS OF A POS-NEG COMBINATION WITH OBJECT AT LESS THAN ONE F.L. FROM LENS

CASE 6



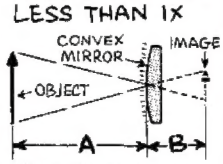
THE NEGATIVE LENS OF A POS-NEG COMBO WITH OBJECT AT MORE THAN ONE F.L. FROM LENS

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	
1	$B=(M+1)\times F$	$B=(M-1)\times F$	$B=(1-M)\times F$	$B=(1-M)\times F$	$B=(M-1)\times F$	$B=(M+1)\times F$	1
2	$B=\frac{F\times A}{A-F}$	$B=\frac{F\times A}{F-A}$	$B=\frac{F\times A}{F+A}$	$B=\frac{F\times A}{F+A}$	$B=\frac{F\times A}{F-A}$	$B=\frac{F\times A}{A-F}$	2
3	$B=A\times M$	$B=A\times M$	$B=A\times M$	$B=A\times M$	$B=A\times M$	$B=A\times M$	3
4	$A=\frac{B}{M}$	$A=\frac{B}{M}$	$A=\frac{B}{M}$	$A=\frac{B}{M}$	$A=\frac{B}{M}$	$A=\frac{B}{M}$	4
5	$A=\frac{F}{M}+F$	$A=F-\frac{F}{M}$	$A=\frac{F}{M}-F$	$A=\frac{F}{M}-F$	$A=F-\frac{F}{M}$	$A=\frac{F}{M}+F$	5
6	$A=\frac{F\times B}{B-F}$	$A=\frac{F\times B}{F+B}$	$A=\frac{F\times B}{F-B}$	$A=\frac{F\times B}{F-B}$	$A=\frac{F\times B}{F+B}$	$A=\frac{F\times B}{B-F}$	6
7	$M=\frac{B}{A}$	$M=\frac{B}{A}$	$M=\frac{B}{A}$	$M=\frac{B}{A}$	$M=\frac{B}{A}$	$M=\frac{B}{A}$	7
8	$M=\frac{F}{A-F}$	$M=\frac{F}{F-A}$	$M=\frac{F}{A+F}$	$M=\frac{F}{F+A}$	$M=\frac{F}{F-A}$	$M=\frac{F}{A-F}$	8
9	$M=\frac{B-F}{F}$	$M=\frac{B+F}{F}$	$M=\frac{F-B}{F}$	$M=\frac{F-B}{F}$	$M=\frac{F+B}{F}$	$M=\frac{B-F}{F}$	9
10	$F=\frac{A\times M}{M+1}$	$F=\frac{A\times M}{M-1}$	$F=\frac{A\times M}{1-M}$	$F=\frac{A\times M}{1-M}$	$F=\frac{A\times M}{M-1}$	$F=\frac{A\times M}{M-1}$	10
11	$F=\frac{B}{M+1}$	$F=\frac{B}{M-1}$	$F=\frac{B}{1-M}$	$F=\frac{B}{1-M}$	$F=\frac{B}{M-1}$	$F=\frac{B}{M+1}$	11
12	$F=\frac{A\times B}{A+B}$	$F=\frac{A\times B}{B-A}$	$F=\frac{A\times B}{A-B}$	$F=\frac{A\times B}{A-B}$	$F=\frac{A\times B}{B-A}$	$F=\frac{A\times B}{A+B}$	12

CASE 1 — Two Cases: When **A** IS BETWEEN **F** and **2F** (shown), THE SYSTEM IS PROJECTION -- THE IMAGE IS LARGER THAN OBJECT. When **A** IS MORE THAN **2F**, **B** WILL BE LESS THAN **2F** and THE IMAGE WILL BE SMALLER THAN OBJECT. _A CAMERA IS A COMMON EXAMPLE_

CASE 2 — THE IMAGE IS VIRTUAL, ERECT and MAGNIFIED. **M** IS NEVER LESS THAN 1X ... IS GREATEST WHEN OBJECT DISTANCE (**A**) IS JUST UNDER ONE F.L. _THIS IS THE OPTICAL SYSTEM OF THE COMMON MAGNIFIER OR READING GLASS_

CASE 3 — THE IMAGE IS VIRTUAL, ERECT and REDUCED. **B** IS ALWAYS LESS THAN **A** and **M** IS ALWAYS LESS THAN 1X

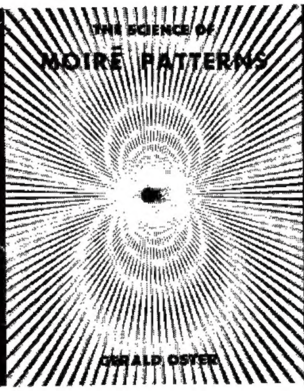


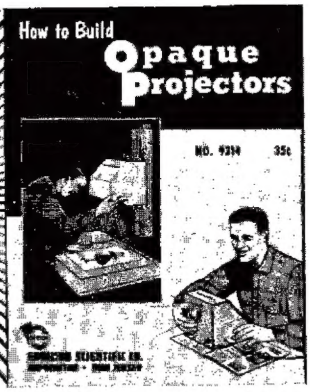
ALL CASES CAN BE WORKED WITH MIRRORS

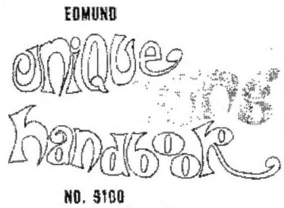
CASE 4 — TWO POSITIVE LENSES WILL HAVE A SHORTER E.F.L. THAN THE FIRST LENS USED ALONE. _THE IMAGE FORMED BY THE FIRST LENS BECOMES A VIRTUAL OBJECT FOR THE SECOND LENS_. _THE SECOND LENS IN THIS SYSTEM IS SOMETIMES CALLED A "BERTRAND" LENS_

CASE 5 — A POS-NEG COMBO ARRANGED IN THIS MANNER WILL HAVE A GREATER F.L. THAN FIRST LENS USED ALONE. _THE SECOND LENS OF THIS COMBO IS OFTEN CALLED A "BARLOW" LENS. NOTE DISTANCE **A** MUST BE LESS THAN THE F.L. OF THE NEGATIVE LENS_

CASE 6 — IF DISTANCE **A** IN CASE 5 IS INCREASED, THE FINAL IMAGE WILL BE VIRTUAL AND TO THE LEFT. _THIS SYSTEM HAS A LONG FRONT FOCAL LENGTH, WHICH IS SOMETIMES A USEFUL FEATURE FOR A LOW-POWER MAGNIFYING GLASS_







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